HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

A Review of the Scientific Literature related to the Principles and Practice of Habitat Restoration

September 1, 1996

Prepared by a Team of Bay-Delta Stakeholder Scientists

Team Chair

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This report was prepared in support of the CALFED effort to develop a comprehensive ecosystem restoration plan for the Sacramento-San Joaquin San Francisco Bay-Delta, and represents the opinions of its authors only. It does not necessarily represent the opinions of the CALFED Stakeholders or any member agency of the Stakeholders.

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THE SCIENTIFIC BASIS FOR HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

Preface

This report consists of two independent but related papers, intended to serve as a general review of the subject of habitat restoration as a means of protecting and/or rehabilitating species and communities. The first paper, prepared by Dr. William Alevizon of the Bay Institute, is intended to provide a conceptual framework for the subject, while Part 2 provides a comprehensive review of case studies. The two sections are complementary, and most productively used in conjunction with one another.

In preparing this report, there was considerable discussion regarding how to interpret the term "restoration." We chose to view restoration from the perspective of two recent and complementary definitions. The first was provided by the Society for Ecological Restoration (SER):

> "Ecological restoration is the process of renewing and maintaining ecosystem health."

The SER notes that "ecosystem integrity" could be substituted for "ecological health" in this definition. The SER also recognizes that "Some landscapes have been converted to the point that a previously occurring ecosystem, if restored, could not be expected to persist. In such instances, the goal of restoration is to establish another ecosystem that is persistent, functional, and biologically diverse."

A second perspective on ecological restoration is provided by the National Research Council (NRC 1995), which recently suggested that "rehabilitation" is an appropriate term to describe the restoration process. In its recent report on protection and management of Pacific Northwest salmon the NRC defines "rehabilitation" as:

> "a pragmatic approach that relies on natural regenerative processes in the long term and the selected use of technology and human effort in the short term -- rather than attempts to restore the landscape to some pristine former state and rather than on a primary reliance on substitution, i.e., the use of technologies and energy inputs, such as hatcheries, artificial transportation, and modification of stream channels. Rehabilitation would protect what remains in an ecosystem and encourage natural regenerative processes."

From the NRC perspective, restoration of biological communities is like restoration of health following an injury. The goal of medical rehabilitation is to promote restoration

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which is self-sustaining and requires a minimum of on-going treatment -- to make the patient healthy. A physician does not attempt to restore a broken bone to pre-break conditions, but protects the bone from further injury and takes action to ensure that natural regenerative processes support the return of key bone functions. This is the goal of ecosystem restoration.

We have applied these two complementary definitions of ecosystem restoration throughout this report. The term "restoration" is therefore not used to imply a return to a pristine historic condition, but rather to mean the restoration of ecosystem health through the promotion of natural regenerative processes. Conditions in the Bay-Delta reflect a long history of large-scale disturbance of critical ecosystem structure and functions, as well as exotic species introductions; application of this practical restoration goal is therefore probably more appropriate than an effort to restore native biodiversity to the system.

THE SCIENTIFIC BASIS FOR HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

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THE SCIENTIFIC BASIS FOR HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

EXECUTIVE SUMMARY

Habitat loss, degradation and fragmentation are widely believed to be the main cause of the alarming loss of biodiversity seen during the last century throughout the world. Modern conservation efforts are therefore largely focused upon the restoration of lost or damaged habitat.

There are two basically different strategic approaches employed in modern habitat restoration practices. A "single-species" approach is generally used when the primary restoration goal is to increase population levels of particular species. This approach proceeds by attempting to identify and manipulate the few highly specific environmental variables identified as probable "limiting factors" for that population or species. In general, this type of restoration effort highly emphasizes manipulations of structural elements of comparatively small patches of "habitat" on a localized scale.

In contrast, a more comprehensive "ecosystem" approach to habitat restoration directs efforts at much larger scales of biological organization than are generally considered in single-species approaches. Here, broadly defined habitat-types, along with the biological communities they support, are the primary targets of environmental manipulations. Restoration efforts are focused upon restoring the integrity of the processes that create and maintain the key ecological characteristics of major habitat types that comprise the landscape, and ensuring connectivity among them. The goal of ecological restoration at this scale is *generally* to produce self-sustaining systems that approximate the original biodiversity of natural ecosystems. But in highly disturbed systems, restoration of a biologically diverse ecosystem which at least enhances conditions for native species may be the practical limit of the effort to restore pre-disturbance conditions.

The information needed to wisely and productively employ single-species restoration strategies includes:

(a) a good understanding of the main factors responsible for regulating population size in the target species

(b) an ability to efficiently manipulate these in the manner desired, without detrimental effects to other co-occurring species of concern

The scientific literature suggests that these conditions are seldom met; in general, population regulation mechanisms in wild animals are usually varied and complex, and poorly understood. Thus, attempts to selectively optimize environmental conditions for the benefit of a selected suite of species have proven largely unsuccessful in either achieving desired increases in target populations, or in protecting biodiversity.

The information needed to productively employ the ecosystem approach to habitat restoration includes:

(a) an understanding of the processes involved in the natural evolution of the native landscape, particularly large-scale geomorphic processes that created and maintained the key ecological characteristics of major habitat-types

(b) an understanding of the current and pre-disturbance nature, extent, distribution and connectivity of major habitat types, and how human activities have affected these patterns

(c) an ability to manipulate (restore or emulate) elements of the system at a sufficiently large scale so as to achieve restoration goals

Attempting to restore habitats at the scales of ecosystems and landscapes is a relatively recent development, and should be considered a technology still in the early stages of development. Nonetheless, our current understanding of ecological processes, as well as a careful consideration of the comparative successes and failures of prior attempts at habitat restoration at all scales, suggest that the ecosystem approach to habitat restoration is much more likely to produce sustainable benefits to either species of special concern or to the resident biological community, than are single-species strategies. The latter are probably best reserved for "emergency" cases of populations or species that are in immediate danger of extinction and need highly focused efforts that may offer immediate benefits. In this sense, the two approaches should be considered complimentary rather than antagonistic; the ecosystem approach provides the highest probability of sustainable, long-term protection for a broad spectrum of species, while the single-species approach provides a possible means of providing relatively quick relief to dangerously depleted populations or species.

Applications of habitat restoration techniques to aquatic systems offer some unique challenges. The evaluation of the effectiveness of restoration efforts is particularly difficult in aquatic environments, due to the difficulty in accurately assessing the abundance and distribution of organisms. Some experiments conducted under conditions which facilitated accurate censusing of fishes and other marine life have shown that habitat enhancement techniques applied to aquatic ecosystems have the capacity to achieve lasting population gains in target species, or to promote the establishment and long-term viability of complex biological communities.

To further examine the practical application of ecosystem restoration principles to the Sacramento-San Joaquin Bay-Delta ecosystem, a team of nine scientists representing the environmental community and water agency interests in the Bay-Delta reviewed case studies of restoration of aquatic/riparian habitats. Part II of this report summarizes the work of the team analyzing case studies of ecosystem restoration.

After reviewing over 2,000 abstracts and some 700 papers and reports, including numerous compendia, the case-study review team concluded that:

1. **Habitat restoration has the capacity to provide significant fish and wildlife benefits.**

   Virtually every report recorded some level of success -- restoration of functions, initial development of a viable vegetative community, and colonization and use by fish and wildlife. Concerns about habitat restoration focus on the inability of rehabilitated habitat to <u>fully</u> offset losses of similar natural habitat on a 1:1 basis, especially on a short-term basis. Critics of habitat restoration (Zedler and Langis 1991; Hogan and Ingram 1992) nevertheless note that rehabilitated habitats perform many of the functions and have many of the benefits of natural habitats.

2. **The relative success of habitat restoration efforts depends largely upon proper design and execution of a restoration plan.**

   There are numerous examples of restoration failure in the literature -- habitat eroded by flood flows, plants and wildlife which do not colonize as expected, problems associated with exotic invasions. Most of these failures are readily explained by some error in design or implementation. Although site-specific failures are possible, there is reasonable assurance that well-designed and well-implemented restoration efforts will provide significant benefits to plant and animal communities. Success is more likely if restoration addresses the full range of factors influencing biological community viability -- from physical habitat to water chemistry to the impacts of human activities.

3. **Increases in the abundances of localized populations are well documented; however population gains at larger spatial scales are less well defined.**

   Censuses of organisms over large spatial scales are seldom conducted because they are inherently difficult and expensive to design and carry out. Studies to assess the success of restoration efforts generally provide only indirect evidence of "entire species" benefits because:

a. In some cases, the possibility exists that the apparent population "gains" observed at "restored" habitat actually represents a simple relocation of individuals from nearby natural (i.e., unrestored) habitat.

b. Generally, pre-project and post-project monitoring has not been designed to attempt to document effects over the entire geographic range occupied by a targeted species; rather such monitoring efforts are restricted to localized habitat patches.

c. Habitat restoration efforts invariably take place in the context of a changing environment in which unpredictable events are co-occurring with the restoration efforts. There is generally no scientific way to directly distinguish the effects of these multiple alterations in the environment. For example, restoration of spawning habitat for salmon may be readily offset by increased harvest, increased predation, or changes in ocean conditions.

d. The scale of most restoration efforts has been too small to have detectable "entire species" effects.

4. **Restoration has a greater likelihood of success if it is holistic in scope; i.e., based on an analysis of physical structure, hydrologic functions, soil and water chemistry, and biological conditions at both the restoration site and within the ecosystem (Garlo 1992).**

5. **The general approach to restoration should be to allow natural processes to shape habitat and resident biological communities.**

   Effects of restoration efforts will not be static because all biological systems change with time. In many restoration efforts, factors such as floods and fire alter the physical structure of habitat as well as ecological processes, and the biological communities associated with the habitat respond and change. Changes which clearly threaten the viability of an endangered species may require focused management intervention.

6. **Demands for short-term confirmation of the full range of benefits of ecological restoration are often unrealistic.**

   Many ecological processes are relatively slow; thus, it often takes many years to realize the full benefits from restoration. Oaks and sycamores, for example, mature over a period of 50-100 years; seagrass beds may develop over a period of 5-20 years before they support species assemblages similar to those of natural reference sites (Meyer et al 1993).

Based on this review, the team reached the following conclusions regarding application of ecosystem restoration principles and techniques to the Bay-Delta:

1. Habitat restoration in the Bay-Delta is being proposed as a long-term, proactive effort to establish conditions which will renew and maintain ecosystem health and should, as a consequence, enhance the potential for native species to maintain viable populations. Because the purpose is not to mitigate for the loss of a specific habitat or biotic community, the problems associated with *mitigating* for a specific and *new* project do not apply to this effort. There is no inherent need to either design habitats to duplicate a specific reference habitat or to measure success in terms of duplicating such habitats, although such efforts may be part of a comprehensive restoration plan.

   As a result, the Bay-Delta restoration effort can be focused on restoration of many habitat types throughout the ecosystem, the result of which will be a net increase in natural habitat compared to the present condition. Also, an ecosystem approach, emphasizing diversity of habitats and the restoration of system-wide structure and function, is recommended.

2. A comprehensive system-wide habitat restoration effort in the Bay-Delta would probably provide significant benefits to a diversity of biological communities, including benefits to species of concern.

3. Such an habitat restoration effort should address the full range of physical, hydrologic, water quality, biological, and human-induced factors which control the conditions in which Bay-Delta organisms live. Thus, efforts should be based on a thorough, multi-disciplinary, understanding of the ecological needs of the Bay-Delta system.

4. The scope of habitat restoration should be adequate to ensure conditions needed for survival of communities and species of concern throughout their range and under a wide range of conditions.

5. The restoration program should be comprehensive in geographic scope, but flexible in approach. Initial restoration efforts should be widely dispersed and adequate in scope to provide meaningful tests of restoration success. Monitoring should be adequate to permit the benefits of the restoration efforts to be assessed, and to guide later efforts.

   Although monitoring of target species responses will be inevitable when endangered species are involved, monitoring should be focused on scientifically valid indicators of ecological structure and function.

6. Adaptive management should be a feature of the restoration plan but it may not be practical to await scientific certainty before adaptively managing. Many researchers note that pursuing habitat restoration at a landscape scale may be a prerequisite for success, because small "test" efforts may not provide the diversity of functions needed for functioning systems and communities to be established. They also note that the desired effects of restoration may not be realized for many years. Implementing an adequate-scale restoration plan should not be delayed pending results of small tests.

   Therefore, a commitment to adaptive management should not imply that implementation of major program elements will be deferred until we have greater scientific certainty about their results. Further, it is also probably advisable to initiate early adaptive management based on monitoring of ecological functions, rather than awaiting data about long-term population trends, which can be obscured by year-to-year variation.

THE SCIENTIFIC BASIS FOR HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

Part 1: Developing a Conceptual Framework and Guiding Principles

by

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June 1996

1. INTRODUCTION

Human modification of natural landscapes has generally been accompanied by notable declines of both native biodiversity and the abundances of economically valuable species throughout the world. While biodiversity losses have been most publicized for tropical rain forests, the proportionate losses of native species in highly altered temperate systems is comparable, and may be occurring at a faster rate (Moyle and Williams 1990). There is general agreement among biologists that the chief cause of the currently high rate of decline and loss of native species worldwide is the widespread degradation, loss and fragmentation of natural habitats (Ehrlich and Ehrlich 1981; Wilson 1985; Wilcox and Murphy 1985; Ehrlich and Wilson 1991; Soule 1991). Thus, provision of sufficient quantities of suitable habitat is a central focus of modern efforts to prevent species extinction, or to rehabilitate decimated populations.

Where natural landscapes have been highly altered by human activities, habitat restoration - the purposeful re-establishment or emulation of natural environmental characteristics - has become a fundamental and common tool of resource managers. This paper develops a conceptual framework for habitat restoration based upon ecological theory, as well as lessons learned from prior efforts. It seeks to elucidate some general principles that might be useful in guiding successful application of this technology, particularly in aquatic ecosystems.

2. APPROACHES TO NATURAL RESOURCE MANAGEMENT A MATTER OF SCALE

Efforts to protect and/or rehabilitate decimated fish or wildlife populations may be based upon ecological/biological perspectives of quite different scales. Historically, most fishery and wildlife management efforts have adopted a somewhat narrowly focused (the so-called "single-species") approach to species protection and recovery. Here, scientific inquiry and information needs of management programs are directed at the biology and ecology of a few select "target" species, and restoration efforts focused on attempting to identify and provide for the needs of these.

Recently, more comprehensive strategies (the so-called "ecosystem approach") have emerged as a result of growing consensus among biologists that the single species approach has failed in many ways, and that in order to begin to reverse the rates of species extinctions and magnitudes of population degradation now evident in many ecosystems, management and restoration programs need to be developed that operate in the context of biological organization at much broader scales than previous efforts (Noss and Harris, 1986; Hutto et al 1987; Scott et al 1987; Noss et al 1994).

At the ecosystem scale, the protection and/or restoration of all resident species (i.e., communities) is considered a natural outcome of the restoration or emulation of the basic structural and functional characteristic of supporting habitat-types, and the larger scale geomorphic processes that create, maintain, and connect these habitats. Consequently, scientific efforts in restoration programs at such broad scales necessarily focus on the nature and connectivity of broadly defined habitat-types (including their biotic communities) within the larger context of entire landscapes and ecosystems, rather than the particular requirements of a restricted set of target populations or species.

As might be expected, overall restoration goals of comprehensive approaches tend to be considerably broader than those of more narrowly focused strategies, which are commonly oriented solely towards increasing population levels of target species. For example, the holistic goal of restoring the "biological integrity" of ecosystems has been recently articulated by Angermeier and Karr (1994), who equate integrity in this sense with the "wholeness" of the system, including both structural elements (e.g., biological communities) as well as processes (e.g. nutrient cycling). In this view, the goal of ecological restoration is to "produce a self-sustaining system as similar as possible to the native biota" (Angermeier and Karr 1994; p 695).

Ecosystem-level approaches have gained tremendous momentum during recent years. The basic tenet of the ecosystem approach to natural resource management is included in the Endangered Species Act of 1973, which seeks among other things to provide, "a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved" (Endangered Species Act 1973, as amended). Still, the fact remains that ecosystem ecology lags behind population biology in terms of scientific understanding, and the theoretical framework and practical applications of the discipline are relatively undeveloped in comparison with those at simpler levels of organization. For these reasons, some resource managers continue to express concern over the wisdom of an overly rapid shift from traditional single-species management and restoration strategies and practices to those at larger scales.

From a practical standpoint, both single-species and ecosystem approaches to resource management have some common elements. Both frequently include common recognition of a particular underlying problem (e.g., loss of habitat), some common objectives (e.g, recovery of endangered species), and even lead to some of the same general management recommendations (e.g, "habitat restoration").

Nonetheless, fundamental differences between the two approaches have practical repercussions that are far from trivial. The information needs, planning process, geographic scope of efforts, direction of scientific research and public policy, strategic approaches employed, and the prioritization of restoration actions and funding mechanisms can all be expected to differ substantially when the ultimate goal of the restoration effort is the recovery of populations of a few particular species, as opposed to re-establishing intact, self-sustaining ecosystems at landscape scales.

3. THE REGULATION OF ANIMAL POPULATIONS A THEORETICAL FRAMEWORK

To appreciate the utility of habitat restoration strategies as applied at both the species and ecosystem levels, it is useful to briefly consider the development of our understanding of animal population growth and regulation.

Historically, there has been a strong tendency to view natural populations as inherently *equilibrial systems*; that is, numbers of individuals tend to stabilize about an asymptote that represents the "carrying capacity" of the habitat or environment for the species/population in question. General acceptance of the equilibrium paradigm by generations of biologists led to a naive but persistent notion that resource managers should be able to more or less manipulate population densities at will, simply be identifying and manipulating the limiting factor(s) primarily responsible for setting the population asymptote (carrying capacity).

The equilibrial view of population regulation gained a great deal of momentum from the development of the *logistic growth curve,* derived from a relatively simple equation originally developed to describe the growth of human populations (Verhulst 1838; Pearl and Reed 1920), and at one time proposed as a general "law" of population growth (Pearl 1927). Nonetheless, numerous laboratory and field studies conducted over the course of this century have repeatedly demonstrated that organisms with complex life cycles (such as insects, birds, fishes, and mammals) generally displayed population growth patterns that deviated markedly from those predicted by the logistic model. Even when the initial growth stages approximated the logistic curve for such organisms, stabilization at an asymptote never occurred (Lund 1950; Scheffer 1951; Birch 1953b; Newson 1963; Klein 1968;).

Thus, as a general model of population growth, the logistic model has serious shortcomings. Although more sophisticated general models of population regulation have been developed to take into account the effects of such things as time lags between changes in population size and the rate of increase (Wangersky and Cunningham 1956; Maynard Smith 1968), chance (stochastic) events (Pielou 1969), and differential survival among different life stages within a species (Caswell 1989), there remains to date no generally applicable predictive model of animal population regulation.

Critical examination of the general concept of equilibrium in ecological systems has led to the realization that there is no inherent reason to expect animal populations to show stable equilibria (Wiens 1984). Instability may be due to biotic interactions such as predator-prey relationships, or alternately to stochastic events such as unpredictable climatic events (DeAngelis and Waterhouse 1987). A complicating factor in the study of population stability is the spatial scale under consideration. Highly localized, small populations of a particular species may be observed to fluctuate widely, or even go extinct. However, many such subpopulations may be linked through dispersal mechanisms into much larger *metapopulations*, which, at a correspondingly greater spatial scale, appear to remain numerically stable.

What then do we know about the ways in which natural animal populations tend to be regulated? In particular, what stops population growth, and what determines average population size over long periods? Attempts to answer these questions are a relatively recent endeavor (i.e., this century), and several different schools of thought have emerged on the subject. One major line of reasoning centers upon the interactions between populations and environmental factors, primarily weather, food, shelter (a place to live), and enemies (parasites, predators, disease). Here, three views may be distinguished. A *biotic school* of population regulation emphasizes the role of density-dependent (effects varying with population size) factors, primarily natural "enemies" such as competitors, parasites, and agents of disease (Nicholson 1933; Smith 1935; Lack 1954). A *climatic school* emphasizes the role of weather, which at times may act in a density-dependent fashion, and at other times in a density-independent manner (Bodenheimer 1928; Uvarov 1931). A *comprehensive school* attempts to provide a unifying synthesis of the climatic and biotic schools, and considers abundance as the outcome of complex interactions between both density-dependent and density-independent factors - environmental variables that are constantly changing in space and time (Thompson 1929; Schwerdtfeger 1941; Andrewartha and Birch 1954).

A second, and quite different, line of reasoning suggests that populations are capable of regulating their numbers entirely through *intrinsic* mechanisms, without a need to rely on *extrinsic* factors (e.g., enemies or bad weather) to prevent them from over-exploiting their food supplies or other renewable resources (Chitty 1960; Pimentel 1961; Wynne-Edwards 1962). This so-called *self-regulation school* points out that populations are composed of individuals that vary in their abilities to survive and flourish under different conditions, and that the makeup of populations, in terms of both genotype and phenotype, is highly subject to change at different population densities. This leads to regular cyclical changes in population size.

Two major conclusions may be drawn from the preceding discussion. First, wild animal populations generally undergo pronounced and unpredictable population fluctuations, rather than to stabilize around some equilibrial value. This pattern is an inherent feature of the ecology of such species, and not necessarily indicative of, or related to, adverse human impacts. Secondly, there is presently no scientific consensus on the mechanisms and/or factors that are primarily responsible for determining average population densities in animals over long-term periods, nor any single widely applicable general model of population growth or regulation. A number of conflicting theories exist on this subject. It is possible that a number of proposed factors, alone or in combination, might determine numbers in any given case.

The practical consequences of these two simple points are far-reaching in terms of efforts to restore or otherwise manage animal populations. In particular, it seems clear that predictive models of population dynamics need to be developed and refined individually for particular cases, since no widely applicable general model exists. Thus, it is probably neither an effective nor efficient strategy to base species recovery efforts solely or primarily on attempts to determine and individually manipulate a few specific environmental variables (i.e., "limiting factors"). Population regulation mechanisms in wild animals appear to be far more complex and varied than such a strategy accounts for. Secondly, it is probably highly unrealistic to set stabilized population levels as restoration goals, since these appear to seldom if ever exist in nature.

4. THE CONCEPT OF HABITAT RESTORATION AT DIFFERENT SCALES SOME BASIC CONSIDERATIONS

Habitat restoration has become a primary tool of resource managers engaged in species protection/recovery programs at the levels of either single species or entire ecosystems. Nonetheless, there are fundamental differences in the way habitat is defined, and habitat restoration practiced, at these different scales of biological organization.

The term *habitat* is generally used by ecologists to indicate the particular kind of place occupied by a species or community. Thus, it is clearly differentiated from the concept of *niche*, which in its modern usage refers to the sum total of a species' ecological requirements (Hutchinson 1958), including not only living space (habitat), but additionally other relevant "dimensions" (e.g., temperature, moisture, food, enemies, etc.). The Endangered Species Act (P.L. 94-325 as amended) confused this distinction through the introduction of a key term called *critical habitat*, defined in the Act as essentially identical to *niche*.

"Habitat" takes on quite a different connotation when used to refer to the use of living space by a particular *species*, as opposed to the type of place (habitat-type) occupied by a *community* of plants and animals. At the larger scale of communities, ecosystems and landscapes, habitat-types are defined by the common characteristics of places occupied by recurrent assemblages of plants and animals. Here, the landscape is seen as a mosaic of distinct but interconnected habitat-types, each occupied by a somewhat predictable community of organisms that is recognizably different from the communities of other habitat-types. In terrestrial situations, habitat-types are generally defined and recognized on the basis of the dominant plant associations; e.g., marsh, scrub oak, beech-maple forest, etc. In aquatic systems, habitat-types are also generally distinguished on the basis of large-scale structural features, most often in terms of physical characteristics of the water column, the underlying substrate, and the land-water interface.

In contrast to the "habitat-type" occupied by communities, the living space used by any particular species (i.e., its "habitat") is defined quite differently. This, in most cases, is either a limited portion of a single habitat-type (in the sense of the term as defined above) or, alternatively, portions of several adjoining habitat-types. For example, an insect may be restricted to a particular tree in a forest habitat-type, while a co-occurring bird may shelter in the forest but forage widely in nearby open grasslands. In the more extreme example, the "habitat" of salmon extends from mid-ocean to continental upland streams hundreds of miles from the sea. Thus, in its totality, the habitat of any particular species is often unique to that species, and in and of itself unrecognizable as a distinctive feature of the landscape.

These basic differences in the species-oriented versus community-oriented definition of habitat lead to very real practical differences in the information needs, techniques, and expected benefits of habitat restoration practiced at these different scales. The functional unit of the restoration effort differs markedly in the two cases; at the finer scale it is the species itself, whereas at the coarser scale it is the habitat-type, including its entire biological community and functional processes.

5. HABITAT RESTORATION SOME GUIDING PRINCIPLES

When the primary goal of a resource management effort is the protection or recovery of one or a few selected species or populations, productive restoration actions need to be guided by quite specific information, i.e., the primary factors (and their interactions) actually determining the average numbers of a given population. However, in most cases there is generally very limited scientific understanding of these (see Section 3, above). In lieu of such information, manipulations of the environment tend to be guided by simple time-series correlations of species abundances with suspected "key" environmental variables. Cause-and-effect relationships are seldom established, or even amenable to determination, due to insufficient data and/or understanding of the processes involved.

It is usual for habitat restoration at this scale to be highly focused upon modification of structural characteristics of "habitat" (in the species-specific connotation described above) of the target species in small, localized habitat "patches." Larger scale processes that may be vital in controlling the formation and/or maintenance of essential ecological features of the larger landscape have generally been ignored. Often, such efforts are restricted to particular aspects of habitat patches; i.e., replacement of spawning gravel in a particular stream.

This narrowly focused approach may be justified in cases where immediate action is required to rescue a population or species from near-certain extinction, since a "best guess" is probably better than no action at all. Still, it must be recognized in such cases that the scientific basis of the restoration action remains highly tenuous, and that localized, narrowly focused restoration actions remain highly vulnerable to eventual disruption from larger scale processes. Additionally, the optimization of environmental conditions for a restricted suite of species might be expected to negatively impact many others with somewhat different ecological requirements. For these reasons, it should not be surprising that species-by-species management strategies have proven neither efficient, cost-effective, nor capable of preventing additional species from reaching endangered or threatened status (Kohm 1991; Noss and Cooperridor 1994; Part 2, this paper). Additionally, it has become increasingly evident that small fragmented habitat patches are generally incapable of sustainably supporting high levels of biodiversity of an area (Noss 1983; Harris 1984; Soule 1987). Thus, while they may have localized or short-term mitigative value, restoration actions dictated by single-species recovery goals are not likely to result in appreciable gains in the protection or restoration of overall biodiversity, or in restoring the integrity of vital ecological processes (e.g, nutrient cycling). Most species-oriented habitat restoration efforts are simply too spatially restricted and too focused upon a narrow range of structural characteristics to achieve such gains.

In contrast, ecosystem-level habitat restoration efforts generally attempt to rehabilitate or emulate a suite of key structural and functional characteristics of entire habitat-types (e.g., tidal marsh, riparian corridor, stream channel), and ensure connectivity with nearby interactive habitat types. Here, the ultimate goal is usually more related to the restoration of the vital large scale processes that ensure the "health" or "integrity" of large areas of the habitat-type itself, including its ability to once again support the biological community naturally associated with it (Angermeier and Karr 1994), rather than the recovery of a particular small part (e.g., population or species) of that habitat. This approach is particularly appropriate when a primary goal of the restoration effort is the protection of overall biodiversity, since that goal invariably includes conservation of many species of whose ecology little may be known. Ecosystem-level restoration efforts usually target comparatively larger "patches" of habitat over a much broader geographic scale than is generally practiced in single-species efforts. Ensuring the long-term ecological integrity of larger areas inherently reduces the likelihood of extinction of small populations, and leads to the conservation of a wider spectrum of species.

The information needs of ecosystem-level approaches to habitat restoration necessarily differ from those of single-species efforts - how is the system put together, and what makes it "tick" - rather than on the needs of individual species. The underlying rationale for this approach is based upon empirical evidence that particular habitat-types tend to support characteristic assemblages of species, presumably because those are the species best adapted to those particular environmental conditions. It is therefore a reasonable assumption that if the key characteristics of a habitat-type are restored, and the area is accessible to new "recruits", it will in time become occupied by its characteristic community. It has been estimated that such "community-level" conservation strategies may be able to protect 85-90% of the species in an area without the need for assessment of any particular species' requirements (Noss 1987).

Understanding of ecosystem characteristics may be partially gleaned from historical records, and/or through the study of intact "reference" (similar undisturbed) systems. However, it is usually difficult to isolate "fine-grained" functional relationships in these complex systems (e.g., the degree to which a particular ecosystem characteristic affects population densities of particular species or guilds). This limits the applicability of coarse-grained restoration strategies to the goal of providing immediate relief to severely threatened species or populations. Still, as a long term strategy, broader-scale approaches would seem to offer the best "bang for the buck" in terms of preventing future species extinctions or listings as threatened or endangered. As Noss et al (1994; pp 8) point out, "A holistic plan for each ecosystem would require much work but would almost certainly be less costly in time and money than an uncoordinated series of recovery plans and habitat-conservation plans for each individual species". Where obvious sources of mortality have been identified for species of concern, they should be addressed in a manner consistent with the long-term goals of a more comprehensive ecosystem restoration plan.

A final consideration in all environmental manipulations is that it is usually difficult to predict how "restored" habitats will fare over the long term in an environment in which the large-scale geomorphic processes that created and maintained the natural landscape have been severely disrupted. For this reason, it is probably more efficient and effective to restore or emulate key elements of these larger scale processes themselves and let nature do the rest, rather than attempting to "fine tune" small fragmented patches of the environment. At the very least, a landscape-scale perspective of the ecosystem is necessary in restoration planning to ensure that component units (habitats) are considered in the context of the entire interactive complex and configuration of associated habitats, and the larger scale processes that surround, shape, and modify them over time.

Neglecting to appreciate this key point has doomed many restoration projects to continued high maintenance costs, and/or a lack of long-term sustainability (see Part 2, this paper).

6. APPLICATIONS TO AQUATIC ECOSYSTEMS

The term "habitat restoration" in common usage includes a broad variety of strategies and actions, ranging from relatively simple, highly localized actions (e.g., placement of spawning gravel or woody debris in a particular stream) to modifications of entire landscapes over very large scales. While there are relatively few case studies that have thoroughly documented the results of such programs through systematic "before-and-after" quantitative inventories, the limited evaluations that have been performed have suggested varying degrees of success in meeting project goals. A comprehensive review of habitat restoration projects is presented and analyzed in Part 2 of this report. Several general issues of particular concern in applications of habitat restoration techniques to aquatic ecosystems are discussed below.

A fundamental concern over the use of habitat restoration or enhancement techniques in aquatic systems is the degree to which such projects actually increase a given population, as opposed to merely redistributing it. This problem, sometimes referred to as the "production versus aggregation" question, is of particular concern to species protection programs, since redistribution could conceivably take the form of population concentration, thereby exposing otherwise dispersed populations to the threat of greatly increased harvest efficiency or other localized sources of damage. Rigorous scientific investigation of this question has been greatly hampered by the comparative difficulty of obtaining accurate population censuses of highly mobile aquatic organisms such as fishes. A restored habitat may be observed to become occupied by target species, but the question remains, has the increase observed been accompanied by a concurrent population decrease elsewhere?

In most aquatic systems, particularly those of large river systems, this question has not been easy to test, because the population size and distribution is not measurable with sufficient accuracy or precision (see Part 2, this report). Thus, in most freshwater and estuarine systems, evidence of a population increase has been indirect. Simenstad et al (1992, 1996) found that species diversity was higher in rehabilitated slough habitats than in adjacent (connected) sloughs, suggesting that colonization was not a function of re-distribution of adults from adjacent habitat. Landin et al (1989) reached a similar conclusion based on studies in the James River in Virginia, where species diversity was found to be higher at rehabilitated marshes than adjacent marshes.

Additional indirect evidence for population gains rather than redistribution comes from studies at sites which were available for colonization but degraded to the extent that they could not support target species until restored. For example, Hunter (1991) describes re-establishment of the sport fishery in Camp Creek and Bear Creek, Oregon following stream restoration. Within the restricted geographic area of the stream, sustainable trout fisheries have been established where they had not existed for decades.

Trout streams and small lakes, isolated from other habitat and of limited size, offer some of the best examples of population increases for target species. Hunt (1988) documented increases in trout populations in Wisconsin streams following restoration. These populations generally withstand the stress of sustained fishing and recover from year to year. Thus it is reasonable to conclude that there have been long-term population benefits as a result of restoration. Similarly, improvements in spawning habitat were noted to increase lake populations of walleye and smallmouth bass (Bassett 1994). At Sharp Creek, Colorado, Stuber (1985) recorded increases in trout standing stock and a shift in the composition of the community in areas protected from grazing impacts; the rehabilitated habitat appeared to favor the target species. In an isolated coastal stream in Oregon (Mack Creek), habitat restoration increased the number and size of coastal cutthroat trout, which were the only fish species in the system, (Moore and Gregory 1988). This suggests a population response which cannot be explained by redistribution.

Controlled experiments to address the issue of production versus aggregation in restored habitat have been limited. largely because of the inherent problems associated with obtaining accurate estimates of mobile aquatic organisms. Some illustrative examples come from marine environments in which conditions allowed accurate censusing of fish populations. Alevizon et al (1985) and Alevizon and Gorham (1989) conducted a series of experiments with small artificial reefs placed in otherwise structurally simple (i.e., sand/seagrass) habitats in the Bahamas and Florida for the express purpose of addressing several specific questions related to population regulation in some of the more common fishes of the area.

The first question addressed was, in a "restored" area, is there a direct relationship between the amount of habitat (shelter) provided and population size for these fishes? This particular question was addressed by deploying artificial reef units in arrays containing different numbers of reefs in nearby and apparently ecologically identical sites. It was found that the eventual population sizes of the target fishes attained over the course of the experiments appeared to be a direct and simple function of the shelter area available, regardless of reef configuration (Alevizon et al 1985). These results provided a clear and straightforward demonstration of the principle that habitat enhancement techniques have the capacity to increase populations of target species.

The *"aggregation versus production" issue* was approached by deploying identical arrays of small artificial reefs at both a "control" and "experimental" site, located respectively in two nearby and ecologically similar areas off the Florida Keys (Alevizon and Gorham 1989). This experiment directly tested the hypothesis that population increases (as opposed to redistribution) in a defined system could be realized by habitat restoration techniques. The reefs were allowed to establish resident fish populations through natural recruitment processes until no further sustained population growth could be ascertained (about one year). Then, a comparatively large artificial reef was deployed in the center of the "experimental" array, while the "control" array was left unchanged. It was found that the populations of target species more than doubled over the course of the ensuing year at the experimental site, while populations of these fishes remained at about the same level at the control site during the same period. Thus, an overall population increase at the experimental site was evident as a direct result of the addition of new habitat. It is not reasonable to assume that the population increase established at the experimental site came at the lasting expense of more distant populations, when closer and confirmed sources of recruits were observed to reestablish original population densities within a single year.

It is worth noting that even though the habitat provided was quite simple compared to natural habitat, the particular species that eventually occupied a given reef were *not* predictable, even though the reef units were constructed to be identical to one another. The actual species recruited varied among reefs, and seemed to be highly dependent upon the nature of nearby sources of recruits, as well as chance factors ("who" arrived first). Additionally, the more complex experimental reef continued to accumulate species throughout the investigation, and eventually became inhabited by a far more diverse fish assemblage than had been anticipated. Thus, even in this unusual case in which good knowledge of a group of species requirements allowed an educated guess at a suspected limiting resource, the results of habitat manipulation had a number of quite unexpected results in terms of the development and reorganization of nearby biological communities. These results lend support to the general conclusion that even in apparently simple cases, the effects of habitat alteration on nearby communities are difficult to predict.

Finally, it should be mentioned that other experiments directed at this same "aggregation versus production" have had mixed results; some have reiterated the conclusion that artificial reefs may increase fishery production (Polovina and Sakai 1989), while others have concluded that artificial reefs served mainly as aggregators, and resulted in little, if any, sustainable increase in fish biomass (Bohnsack et al 1994).

Artificial reef studies have also been useful in providing a somewhat controlled experimental basis for evaluating the capacity of habitat enhancement techniques to support entire biological communities. Long-term studies of large artificial reefs have demonstrated that they are quite capable of establishing complex biological communities

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that approximate those occupying natural habitats of the area (Shiel and Foster 1992). Such examples provide experimental verification of the principle that it is possible to develop and sustain populations of a diversity of species about whose ecology little else is known, simply by restoring sufficiently large areas that contain or emulate the major ecological characteristics of these species known natural habitats.

What general principles of habitat restoration might we apply to the protection of species and biodiversity in large river systems? One of the fundamental precepts that might be gleaned from the preceding discussions is related to the appropriate spatial scale and breadth of focus of restoration efforts in such systems. Even when the primary goal of the restoration program is the recovery of a particular group of species, it has been suggested that ecosystem-level approaches are preferable, and that the most prudent course of action would be to nest species recovery goals within the framework of a more comprehensive set of ecosystem restoration goals.

A recent analyses of salmon restoration needs in the northwestern United States concluded that, "the basic conservation and management unit for stream systems should be watersheds large enough to support self-sustaining populations of native fish. Within and across watersheds, only an holistic approach which considers the linkages between terrestrial and aquatic systems, can efficiently arrest habitat degradation, maintain good habitat, and restore damaged habitat" (Save Our Salmon 1995; p. 33). In addressing the comparative efficacy of ecosystem versus species approaches, Noss (1995; p 6)) concludes that, "ecosystem conservation ... addresses the primary cause of many species declines (habitat destruction), it offers a meaningful surrogate to surveying every species, and it provides a cost-effective means for simultaneous conservation and recovery of groups of species". In a like manner, a recent report by the National Academy of Sciences (1994 p) emphasizes that, "because aquatic ecosystems are interconnected and interactive, effective restoration efforts should usually be conducted on a large enough scale to include all significant components of the watershed."

7. SUMMARY AND CONCLUSIONS

Habitat restoration is a useful management tool in alleviating or reversing human impacts on ecosystems. Habitat restoration techniques commonly in use today include those targeted at increasing local populations of select species, as well as strategies aimed at restoring self-sustaining natural communities. As generally practiced, the former approach tends to concentrate restoration efforts on rebuilding structural elements of species' habitats on a highly localized scale. In contrast, the latter approach tends to focus on the restoration of large scale processes that allow self-sustaining natural habitat-types and communities to reestablish themselves.

The limitations of our scientific understanding of the factors responsible for the regulation of animal populations, as well as consideration of the effectiveness of prior restoration efforts at different scales, both suggest that efforts to optimize the environment to benefit one or a few species are less likely to produce lasting benefits to target species, or the ecosystems of which they are a part, than are more comprehensive approaches that seek to restore conditions that will sustainably support entire biological communities associated with natural habitat types.

Single-species and ecosystem approaches to habitat restoration should be viewed as complimentary rather than competing, as each is intended for a somewhat different purpose (Noss 1995). Nonetheless, it must be emphasized that current thought clearly leans towards the view that the more narrowly focused the restoration effort, the less likely it is to produce long-term success in species or biodiversity protection.

The determination of appropriate spatial scale of a habitat restoration effort is a key consideration in all restoration programs, and may be facilitated by the study of species-area curves for particular community types. Where protection of overall biodiversity is the primary concern, restored areas should be of sufficient size to realistically support viable populations of most naturally occurring species. If the recovery of particular species is a primary concern, the habitat patch size necessary to support desired average population levels may be inferred from population density estimates of target species in reference systems, or in some cases from historical information.

Habitat types do not exist in isolation in nature - they are components of larger landscapes or ecosystems. Failure to understand interactive processes among different habitat types may severely limit the effectiveness of restoration efforts at any scale. In particular, failure to place localized restoration efforts in a landscape context may lead to less than satisfactory results, because large-scale processes are likely to eventually prohibit or inhibit long-term viability of localized environmental modifications.

It is essential that restoration goals be established that are both appropriate and scientifically defensible, as well as compatible with the principles, techniques, and limitations of habitat restoration as practiced at any scale. This key point is emphasized in a recent report by the Ecological Society of America (1996), which warns against the establishment of natural resource management strategies based upon "statements of need or want such as mandated timber supply, water demand, or arbitrarily set harvest limits of shrimp or fish. Rather, sustainability must be the primary objective, and levels of commodity and amenity provision adjusted to meet that goal".

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THE SCIENTIFIC BASIS FOR HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

Part 2: Analysis of Case Studies

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THE SCIENTIFIC BASIS FOR HABITAT RESTORATION IN AQUATIC ECOSYSTEMS

INTRODUCTION

A. Background: Habitat Restoration as a Feature of a Comprehensive Bay-Delta Plan

On December 15, 1994, major urban and agricultural water agencies and environmental groups reached agreement with state and federal regulatory agencies on an interim solution to a number of environmental problems in the Sacramento-San Joaquin Bay-Delta ecosystem (hereafter "Bay-Delta"). This interim solution provided for increased Bay-Delta outflows during the February - June period and modified the operation of Central Valley Project (CVP) and State Water Project (SWP) facilities. The terms of this interim solution were later adopted by the California State Water Resources Control Board.

This interim solution was intended to enhance conditions for fish and wildlife in the Bay-Delta, pending development of a more comprehensive long-term plan that would include restoration of habitat in the Bay-Delta. A 7-agency state-federal entity (CALFED) was established to develop such a comprehensive plan, with the assistance of the various "stakeholders" in the Bay-Delta and its tributary watersheds.

B. Purpose of this Literature Review

Early in the CALFED planning process, four questions about the role of habitat restoration in the comprehensive Bay-Delta plan were raised:

a. What is meant by habitat "restoration" or "restoration"?

b. What can we expect from a program of habitat restoration -- does it work?

c. To what extent should habitat restoration be pursued in the Bay-Delta?

d. Could a comprehensive program of habitat restoration substantially offset the impacts of SWP/CVP operations?

This literature review was intended to address the first two questions, to the extent feasible, by reviewing habitat restoration projects documented in the published scientific literature and in available government and industry reports. The third question is addressed in general terms. The ability of a habitat restoration program to offset impacts of SWP/CVP operations will depend on how the habitat restoration is combined with modifications to SWP/CVP operations and facilities.

C. Key Definitions and Typical Restoration Project Descriptions

To understand the literature on this subject, it is important to define the key terms of the assignment and to describe the focus and scope of a typical river, lake, wetland, or nearshore ocean restoration.

1. Habitat

Habitat restoration/restoration programs have addressed a virtually all factors affecting the health of the resident and transitory members of biological communities. Factors mentioned in the literature include, but are not necessarily limited to:

a. Physical characteristics: size, shape, depth, slope, altitude/elevation, aspect, interconnectedness, complexity, and other physical features;

b. Water and air temperature;

c. Water quality parameters: dissolved oxygen, toxics, pollutants, turbidity, and suspended and dissolved nutrient loads;

d. Characteristics of soil/substrate: sediment size and transport, organic carbon and nutrient concentrations, exposure to forces from currents and waves;

e. Characteristics of flow: timing, volume, rate, and spatial pattern; depth and duration of inundation;

f. Tidal influence;

g. Vegetative elements: community type, species composition and dominance relationships, horizontal and vertical structure, density, presence of large woody debris, and percent cover;

h. Sources of mortality: commercial and recreational harvest, diversions, predators, poachers, and others;

j. The structure of the aquatic community: dominance, predator-prey relationships, food sources and pathways, and competitive relationships.

In short, habitat may be defined as "the biotic and abiotic conditions in which an organism lives," and habitat restoration may address all of the factors listed above. Habitat restoration may thus include actions such as screening a water diversion (which will alter a number of related conditions), removal of toxins, or development of a specific type of physical habitat.

3. Fish and Wildlife

For purposes of describing animal communities at all levels, we have adopted the California Fish and Game Code usage of "fish and wildlife" as an inclusive term covering all animal species at all trophic levels.

4. Typical Restoration of Rivers and Streams

Rivers and stream restoration most often involves efforts to restore the natural diversity of habitats lost as a result of sedimentation, channelization for navigation and flood control, and loss of adjacent riparian habitat due to activities such as logging, grazing, and agriculture. Common restoration actions include:

a. Watershed management actions to reduce erosion and sediment inflow to the river or stream;

b. Replanting of riparian vegetation to restore bank integrity and reduce stream temperatures;

c. Placement of woody debris and a variety of rock structures into the stream to re-create a complex system of riffles, pools, and backwater effects and thereby restore conditions needed for a diverse community;

d. Removal of levees to allow the river or stream to meander, thereby creating a diverse complex of shallows, pools, bank undercutting, sand bars, ox-bows, wetted islands, and seasonally-flooded marshes; and lengthening the river to return flow velocities to a more natural regime; and

e. Pollution control to restore water quality.

A common goal of these restoration actions is to restore water quality, natural structures, and flow dynamics to the rehabilitated river or stream, thereby creating a range of water depth, clarity, temperature, turbidity, flow velocity, sediment transport, substrate conditions (such as gravel beds), bank stability, and vegetative cover and structure which reflects conditions in natural rivers and streams. The biological benefits of these actions depend on the particularities of the restoration. Some restoration programs have been aimed at enhancing conditions for a single species, such as salmon or trout; others have been aimed at restoring biodiversity and whole communities. A common element of many river and stream restoration projects is restoration of the riparian zone adjacent to the water way; this restoration of "shaded riverine aquatic" habitat significantly alters in-stream conditions.

5. Typical Restoration of Lakes

The most common problems in lake ecosystems are: a) eutrophication due to increased nutrient loads from pollutants, fertilizers, and detergents; b) impacts from introduced species; and c) rapid sedimentation resulting from nearby development. Common restoration actions include:

a. Pollution and runoff control, including regulation of adjacent land uses and discharges and erosion control efforts;

b. Dredging to remove sediment loads, increase depth;

c. Planting of marsh and riparian zones around the lake to reduce sediment and nutrient inflow to the lake;

d. Oxygen enhancement, using aerators;

e. Harvest of aquatic plants, particularly exotic plants such as lotus;

f. Control/removal of exotic species, either through poisoning or changes in harvest regulations; and

g. Enhancement of flows into the lake.

A common goal of these programs is to enhance water quality and thereby recreate conditions favorable to either native and/or desired game fish. Initial responses are often measured in terms of ecosystem functions, such as reductions in algal blooms, increases in water clarity, and decreases in dissolved nutrients with increases in dissolved oxygen.

6. Typical Restoration of Wetlands

There are many different wetland communities, from seasonally-flooded wetlands such as vernal pools and off-channel bottom-land forests to permanently flooded tidal and subtidal marshes. Wetlands are commonly rehabilitated to offset the impacts of development on natural wetlands/marshes.

Wetland restoration projects have occurred in abandoned strip mines, landfills, and gravel pits; along and within dredged channels; in areas where wave action and boat wakes have eroded habitat; in harbors; and in bays and estuaries where pollution, sedimentation, dredging, and spoil disposal have destroyed natural marshes. Common restoration actions include:

a. Removing levees to reconnect an area to an historic source of water; this may be combined with extensive re-contouring and/or filling of the land to approximate the physical characteristics (slope, depth, channels) of a natural wetland;

b. Removal of exotic plants and replanting with appropriate species;

c. Protection of wetlands from erosion, wave action and flood flows with a variety of berms and barriers; and

d. (Less commonly) stocking with native fish and invertebrates.

The general goals of wetland restoration projects are reestablishment of a plant community similar to some natural "reference" community and reestablishment of "natural" hydrology and hydraulics within the rehabilitated area. In many programs evaluated, the goal of the wetland restoration program was to recreate the conditions and the biological community at a nearby "natural" wetland which would be lost due to a development project.

Some wetlands have been specifically designed to function as fish and wildlife habitat and as sewage treatment or flood runoff treatment facilities.

7. Typical Restoration of Nearshore (Reef) Habitat

The most common problems addressed by nearshore habitat restoration projects are physical modification due to erosion, sedimentation, dredging, and spoil disposal; impacts from large-scale trawling; and impacts from pollution and sedimentation. Nearshore reef restoration may range from placing layers of clam shells on mud flats to extensive and carefully engineered projects to create complex coral reefs. Actions taken generally include:

a. Placement of some structure at a target depth, using tires, floating platforms, concrete rubble, fabricated block, clam shells, old automobile bodies, sunken ships, and other "clean" debris;

b. Action to control shoreline erosion and/or pollutant discharge; and

c. (Less commonly) initial planting with a key species, such as giant kelp.

A common goal in these programs is the creation of a structure and substrate which will provide shelter, foraging areas, and nursery areas for a wide range of fish and invertebrates. Some reef projects are targeted at a single species, such as lobster, and reef structures contain pre-fabricated shelters (tubes for example) for this species. Other projects are aimed at the broader community and are more randomly structured (such as mounds of concrete rubble).

SCOPE OF THE REVIEW

A. Organization of the Review

A general review of the foundations and principles of habitat restoration and ecosystem management was conducted by Dr. William Alevizon of The Bay Institute (Part I of this report).

Part II of this report covers the practical applications of habitat restoration, evaluating case studies from throughout the world. Table 1 (tables are at the end of the report) describes the organization of the review team.

B. Review Effort

General

A systematic search of the relevant scientific literature was conducted. The focus was on habitat restoration efforts related to wetlands and other fisheries habitats, which narrowed the scope of the search significantly. The review included incidental upland and riparian habitat restoration efforts; but a focused search for documentation of such projects, which may number in the tens of thousands worldwide, was beyond the scope of this review.

The review began with a search of several large data bases:

1. The Knight-Ridder Dialog data bases

   - BIOSIS Previews
   - NTIS
   - Oceanic Abstracts
   - Enviroline
   - Aquatic Sciences and Fisheries Abstracts
   - CAB Abstracts
   - GeoArchive
   - Environmental Bibliography
   - Water Resources Abstracts
   - GEOBASE

2. National Information Services Corporation

- Water Resources Abstracts, Vols 1 and 2
- Marine, Oceanographic, and Freshwater Resources
- Aquatic Biology, Aquaculture, and Fisheries Resources

3. The Fish and Wildlife Reference Service

4. Bibliographies prepared by others (Matthews and Minello 1994; Erwin 1996)

From these sources, approximately 8,000 potentially relevant titles were identified, which were then screened to approximately 2,000. Abstracts for these 2,000 titles were obtained and reviewed, producing a list of approximately 700 documents for review (see attached bibliography). The review team abstracted approximately 200 of these documents, with an emphasis on case histories where rehabilitated habitats were (a) compared to reference natural habitats and/or (b) changes in plant and fish and wildlife communities were monitored.

Data Base Limitations

1. General

Most restoration projects have been mitigation efforts. Mitigation is intended to offset impacts from development and few mitigation agreements have required monitoring of pre-project conditions, post-project conditions, and conditions at a comparable nearby reference site. As a result, ". . . experience and the available science base on restoration and creation are limited for most types [of habitat restoration] and vary regionally" (Kusler and Kentula 1990).

Where monitoring has been performed, it generally lasts less than three years (Josselyn et al 1990), which is not adequate to track the maturation of habitat and the initial development of communities. As a result, evaluating the benefits of habitat restoration is often based on "early returns." Nevertheless, the literature contains several hundred examples of restoration projects which report the results of 1-3 years of monitoring, and a number of reports which cover much longer periods, most involving re-investigation of restoration sites from 5 to 20 years following the initial restoration and monitoring. These provide a basis for drawing general conclusions about the potential benefits of restoration efforts. Predictions about the benefits of any specific Bay-Delta restoration effort will require an understanding of the ecological context of the restoration and detailed site-specific data.

2. Incomplete Data Sets

Results reported often appear influenced by the focus of the mitigation effort. In some cases, detailed vegetative community data were available, but the researchers failed to collect, or report, data on use of the habitat by fish and wildlife. For example, Matthews and Minello (1994) reviewed 787 marsh enhancement projects from Maine to Texas and found animal use of the habitat documented for only 25 projects, or 3% of the total. Less frequently, there was extensive documentation of fish and wildlife use, but no discussion of vegetative communities. Data on physical, hydrologic, biochemical, plant, and animal responses to restoration were available in few papers and reports, primarily those describing large-scale mitigation and dredge spoil projects of the U.S. Army Corps of Engineers (USACE).

The type of habitat restored also appears to influence the type of data available. Stream, lake, and reef restoration reports infrequently report vegetative data, but frequently report colonization by fish and invertebrates. In contrast, wetland and marsh restoration projects routinely report vegetation data, and less frequently report data on fish and wildlife populations, although avian inventories are often an element of such reports. Much of this inconsistency is related to sampling difficulty and/or the need for additional data. Fish are difficult to sample on reefs and in vegetated shallow-water habitat. Vegetation is difficult to sample in turbid and fast moving rivers and streams. The data in a given report are therefore often ecologically incomplete.

3. Data on Seasonally-Flooded Waterfowl Habitat

Successful restoration of seasonally-flooded migratory waterfowl habitat is well documented. The restoration of these habitats is practiced routinely throughout the world, using a variety of low-cost, low-technology techniques. There is also extensive, long-term experience with these habitat types in the Bay-Delta, with both private landowners and State and Federal agencies involved seasonally-flooded waterfowl habitat restoration. This habitat is relatively easy to rehabilitate, provided underlying soil and hydrologic conditions are appropriate. Therefore, we did not systematically search for data on this type of restoration, although the reader will find a few incidental references to interesting examples of this type of work in the summary tables at the end of this report.

CASE STUDIES: RESPONSES TO HABITAT Restoration

A. Response Categories

Four levels of response to various habitat restoration programs were identified and evaluated:

1. Restoration of habitat or ecosystem functions: Did the restoration effort lead to desired changes in the structure and functioning of the physical environment, such as changes in water quality or tidal interchange?

2. Restoration of plant communities: Did desired vegetation grow, and did it evolve to resemble natural reference communities -- in both form and function?

3. Restoration of animal communities: Did fish and wildlife use the rehabilitated habitat and did the community of animals evolve to resemble natural reference communities? Is there evidence that local increases in abundance and use reflect a net increase in population size?

4. Potential incidental benefits: Did the project also provide water quality, water supply, or flood control benefits?

B. Restoration of Habitat or Ecosystem Functions

<u>Review of Results</u>

Restoration of important physical, chemical, hydrologic, and biological functions is well documented. Provided the restoration is well thought-out, sited appropriately, and implemented according to plan, it appears feasible to rehabilitate functions such as seasonal streambank overflow (Gildersleeve 1989), interchange and sediment transport between a marsh and an adjacent stream channel (Steinke 1986), a more diverse hydrologic regime in a previously channelized stream (Jungwirth et al 1993), and tidal exchange (Caiazza 1989; Chamberlain and Barnhart 1993; Niesen and Lyke 1981; Novick and Hein 1982; Peck et al 1994; Kurz et al 1995; Bell and Vose 1992; Niesen and Josselyn 1981; Ecoshore, Inc. 1992).

Much of the literature is focused on reporting the biological response to a restoration program, and there are often no detailed descriptions of the physical, hydrologic, and chemical dynamics of the rehabilitated site. Nevertheless, the literature contains many descriptions of key functions restored in riverine, wetland, estuarine, and oceanic

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environments. Among the habitat functions documented to result from habitat restoration were:

1. *Restoration of normal temperature regimes.*

   Temperature regimes can be modified by channel deepening, riparian habitat restoration, riffle-pool creation, placement of large woody debris, and dredging.

2. *Increases in habitat diversity.*

   Habitat diversity can be increased through physical re-configuration, dredging and spoil disposal, altering hydrologic regimes, barriers, elimination of grazing impacts, and restoration of meanders.

3. *Reductions in toxics from mine or agricultural discharges.*

   Several studies suggest that physical habitat restoration has effectively treated (bio-remediated) mine or agricultural discharges (Lacki et al 1992).

4. *Restoration of water quality.*

   A number of studies document water quality responses to habitat restoration efforts, often as a result of vegetation-driven changes in nutrient cycling and sediment transport. Beneficial changes in salinity, turbidity, suspended sediment load, and temperature have been noted.

5. *Restoration of tidal influence.*

   Many marsh restoration projects have noted that normal tidal processes can be restored relatively easily, including sediment scour which creates meandering channels across a tidal plain, variable salinities in previously brackish marshes, enhanced dissolved oxygen levels, and tidal flushing of contaminants and other organics from marshes.

6. *Restoration of sediment regimes.*

   Properly designed projects may restore natural accretion and scour regimes in rivers, lakes, and estuaries.

7. *Restoration of groundwater levels.*

   Groundwater exchange between rivers and adjacent wetlands, and in wells adjacent to marshes, has been improved.

8. *Restoration of estuarine functions.*

   Stable marsh, shallow reef, and mudflat/channel structures have been successfully restored. Near natural salinity and temperature regimes have also been noted.

9. *Restoration of reef structures -- shelter and substrate.*

   Reefs are routinely rehabilitated throughout the world, providing varied habitat with shelter and attachment substrate for many organisms. The structural integrity of artificial reefs has been demonstrated in rubble-mound, tire, and block reefs.

10. *Restoration of riverine and marsh hydrologic regimes.*

    In small streams, deep channels with riffle-pool structures can be restored readily, even in areas of mine slag and other highly disturbed areas. Channelized rivers can be restored to sinuosity, with accompanying riffle-pool complexes, bars, and oxbows. These changes result in more natural flow regimes, timing, duration, and variability. Restoration a natural marsh hydroperiod has been documented in a number of studies, for example Devroy and Hanners (1988).

11. *Restoration of wetland functions.*

    Freshwater, brackish, and salt water marshes have been successfully restored. This includes the establishment of organic soils on inorganic dredge spoil and mine tailings as a result of planting of wetland plant species (Banner 1977; Reed and McLeod 1994; Cammen et al 1976; Cole 1978).

The ability to engineer changes in the physical, hydrologic, and chemical functions of a variety of habitats is the basis for all habitat restoration. Initially, it must be possible to stabilize the physical habitat and reestablish key processes to promote growth of desired plant communities. Both of these objectives have frequently been accomplished (Table 2).

Applications to the Bay-Delta

The experience of others suggests that it is feasible to rehabilitate riverine and estuarine habitats, and that restoration projects can result in the re-initiation of natural processes, such as seasonal overbank flows, scouring of fines from gravel beds, restoration of meander functions, enhancement of water quality, and creation of riffle-pool complexes. Restoration necessary to accomplish these effects may range from removing a source of impact to complete re-construction of a site, including re-contouring land and changing the hydrology. Regardless of the level of effort required, there is little doubt that physical and hydrologic conditions needed by Bay-Delta species can be rehabilitated.

Restoration of such functions requires careful planning, and site conditions must be appropriate to the function desired. Stable shallow-water habitat cannot be subject to high wave energies or constant boat wake effects which can cause erosion before plants have an opportunity to "take." Thus, for example, habitat restoration in Frank's Tract would require engineered islands to break up waves generated by the frequent high winds in the Bay-Delta. Water-side levee enhancements may also require at least temporary protection.

C. Restoration of Plant Communities.

Review of Results

Case studies of the recovery of plant communities in rehabilitated riparian wetlands, estuaries, and marshes commonly include data on vegetation, because changes in plant communities are relatively easy to detect and changes in community are easily described in terms of simple statistics such as percent cover, total biomass, and species composition (Table 3). Plant community restoration is less well documented for rivers, lakes, and reef communities.

The two key issues in plant community restoration are:

1. Whether the communities established are similar in plant composition, structure, density, and biomass to those of comparable natural habitats;

2. The time it takes from initial colonization to development of habitats comparable to natural ones.

Most restoration research has identified differences between rehabilitated and natural plant communities in terms of:

1. Species composition. In some cases, rehabilitated areas have similar or greater plant diversity (Havens et al 1995; Fonseca et al 1996), which may be a result of the rehabilitated area being in the early stages of succession. Naturally recovering plant communities, such as chaparral, often have similar high diversity stages during early recovery, and become more monotypic as they grow older. In some other cases, restoration results in monotypic plots, possibly because planted vegetation dominates rapidly and overwhelms competition.

2. Plant density. Results of studies vary, with some finding plant density lower than that in reference habitats (Dibble et al 1995) and some finding higher densities in the rehabilitated plots (Minello and Zimmerman 1992). There is no readily apparent explanation for these variations, which may depend on pre-planting soil or other site conditions.

3. Biomass. Within 1 to 3 years following restoration, biomass above ground tends to be equivalent or higher in rehabilitated communities than in natural communities (Minello and Zimmerman 1992; Minello and Webb, Jr. 1993; Levin et al 1995), but this trend is reversed for below-ground biomass (LaSalle 1995; Simenstad et al 1993). This is a phenomenon common to many artificially propagated plant communities, from commercial crops to home gardens; above-ground growth proceeds at a higher rate than root growth in early growth periods, but the ratio of above-ground to below-ground biomass shifts as plants mature. Anyone who has planted tulips, and then re-planted them at a later date, has noticed this shift in biomass distribution.

4. Community structure. Dominant plants in natural plant communities also tend to be dominant in properly designed and implemented rehabilitated communities (LaSalle 1995; Havens et al 1995; Fonseca et al 1996). That is, if the physical, hydrologic, and chemical conditions are appropriate for the growth of a naturally dominant plant, then it will outcompete and displace plants not as well adapted to these conditions. A number of studies note shifts in plant community composition and structure following restoration of physical, hydrologic, and water quality parameters similar to those found in natural habitats (Simenstad and Thom 1996).

In summary, for most of the studies reviewed, the authors have concluded that the rehabilitated plant community often resembles natural reference areas in many ways, even in early stages of development. This is particularly true of areas which are naturally colonized following restoration of natural physical structure and hydrodynamic function.

Time also appears to have an influence on the results. The greatest differences between rehabilitated and natural habitats appear to occur in the early developmental stages. Where researchers have re-sampled a site 5-20 years following initial restoration, they have often found self-sustaining habitats which closely resemble natural reference habitats (Anderson and Ohmart 1985; Hunter 1991; Sacco et al 1994).

Applications to Bay-Delta

It should be feasible to rehabilitate plant communities in upland, riparian, and freshwater and estuarine aquatic habitats in the Bay-Delta, with virtually immediate benefits to fish and wildlife. Restoration of a full range of habitats and functions will require up to 10-15 years for communities to mature.

D. Restoration of Fish and Wildlife Communities

Review of Results

In this review, we focused on aquatic communities because there is greater controversy surrounding their response to restoration than there is for terrestrial and riparian communities. Aquatic animal communities, particularly fish communities, are difficult to sample, particularly in heavily vegetated, large areas. Streams and small lakes do not have this problem, but adequate sampling in large rivers, freshwater marshes, estuaries, and oceanic areas is extremely difficult. In the review of the response of aquatic animals to habitat restoration, we also focused on two separate issues:

1. Did aquatic fauna use the rehabilitated habitat and did the community of animals evolve to resemble natural reference communities?

2. Is there evidence that this use constitutes a net increase in local populations or has population-level benefits?

Evidence of aquatic faunal use of rehabilitated habitat is universal, but evidence of population-level benefits is not well documented. Changes in the physical components of habitat have been shown to have almost instantaneous "fish attraction" effects, with rapid colonization and use of virtually any structure which offers food, cover from predators, and the ability to reduce energy expended swimming. Fish will congregate rapidly at artificial reefs, under floating pontoons, in imitation (plastic) seagrass, around pilings, and near any vegetation which offers cover.

This tendency to aggregate near elements of structure (commonly referred to as fish attraction devices or "FAD's") raises the question of whether fish which use rehabilitated habitats have merely moved from one habitat to another, with no net effect on populations. In this review, we searched for data which would indicate whether occupation or use of rehabilitated habitat was merely a redistribution of existing populations or represented a potential increase in local populations.

Given that overall population effects are difficult to assess in any biological system because measuring an entire population is difficult, the question of population-level effects from habitat restoration is often addressed indirectly. There are a number of ways in which rehabilitated habitat could have tangible benefits to a species or community which would logically lead to net increases in populations, given no offsetting impacts outside of the local area studied.

In reviewing the literature to determine the response of aquatic fauna to habitat restoration, then, we searched for direct evidence that populations were expanding and evidence that the rehabilitated habitat provided specific benefits to various life history stages of aquatic fauna.

Indicators of Population Expansion

1. Did fish and/or other aquatic species use the rehabilitated habitat?

Virtually all researchers report that fish and other aquatic species colonize rehabilitated aquatic habitats rapidly (Table 4). The initial colonization almost always consists of motile species swimming or crawling to the rehabilitated habitat area. Following this initial stage, there is evidence of colonization by drifting eggs and larvae, and by reproduction. See, for example, work by Simenstad and others in Washington (for example Simenstad et al 1992 and 1996), Lindberg and Marzuola (1993), Bailey-Brock (1989), Collins et al (1990), Hanlin et al (1994), and Caiazza (1989), who all make note of the rapid recolonization process. The phenomenon occurs in a variety of habitats and for many species, from invertebrates to salmon smolts. Although herptofaunal colonization is often a problem, Lacki et al (1992) document successful colonization by herptofauna (tree frogs, pickerel frogs, snakes) in wetlands established to treat mine drainage.

Where rehabilitated habitat is used for spawning or is in the path of drifting eggs, larvae, seeds, or other propagules, colonization may also occur without redistribution of plants, fish, and other animals from adjacent habitat. This type of colonization is documented in reefs, intertidal zones, rivers, and marshes (Morrow et al 1995; LaSalle 1995; Streever and Crisman 1993; Landin et al 1989; LaGrange and Dinsmore 1989). In many cases, the evidence for non-redistributive colonization is indirect, such as different species composition at the rehabilitated wetland compared to the adjacent reference areas. There were few reports suggesting habitat use was limited to only a few species; in these cases, the authors frequently note that project design was flawed.

2. Did natural reference habitats surveyed suffer any noticeable declines in population as a result of the restoration of habitat nearby?

Most studies for which there was a nearby natural reference system show no changes in the community composition, in target species populations, or in individual species age structure when habitat is rehabilitated nearby, or even immediately adjacent to, natural habitat (Shirley 1992).

It should be noted, however, that there were few pre-project/post-project surveys of reference habitats. However, there are indications in some studies that fish migration from reference areas was not occurring. Motta (1985) sampled pre-project and post-project, and noted fish assemblages in the rehabilitated mangrove-dominated lake were similar to natural marsh. And many researchers note that densities in rehabilitated habitat are lower in early stages of colonization (Levings and McDonald 1991) but become equivalent slowly, suggesting reproduction rather than recolonization. Other studies note higher densities of non-motile (sessile) species in rehabilitated habitat than adjacent natural habitat, while motile species remain in the natural habitat (Rutherford 1989). And several long-term studies show that natural and rehabilitated marshes eventually come to resemble one another (Allen et al 1994; Sacco et al 1994).

Perhaps the strongest evidence for increases in population rather than redistribution effects comes from studies involving sites which were connected to viable habitat but were degraded to the extent that they could not support target species. For example, Hunter (1991) and Sparks (1992) describe re-establishment of sport fisheries in Camp Creek, Oregon and the Illinois River following restoration. At these sites, fish migration was always feasible, but self-sustaining populations could not be developed because of physical (Camp Creek) and chemical (Illinois River) degradation. In addition, improvements in spawning habitat were noted to increase lake-wide populations of walleye and smallmouth bass (Bassett 1994).

Finally, studies on coral reefs (Alevizon et al 1985) have demonstrated redistribution from natural to rehabilitated habitat is followed by increases in abundance and density of fish and other organisms on both sites, evidence of a net increase in the local population as a result of increasing habitat availability. Alevizon and Gorham (1989) further demonstrate that increases in populations on artificial reefs can be accomplished without changes in the density or abundance of species on nearby habitat, suggesting a net gain in local population. However, Bohnsack et al (1994) found that a majority of artificial reef biomass comes from colonizers, not fishes settling as larvae and developing.

Therefore, while it is clear that initial recolonization may draw motile species from nearby habitats, there is evidence which suggests there are net gains from habitat restoration.

<u>Indicators of Habitat Benefits from Rehabilitated Habitats</u>

1. Did the assemblage of fish and other aquatic species in rehabilitated habitat resemble the assemblage in natural reference habitats?

   Similar community composition is an indication that the habitat is functioning naturally and providing conditions which at least mimic natural conditions.

   A number of studies indicate that aquatic faunal communities in rehabilitated habitat evolve to resemble communities in natural reference habitats (Roberts 1991; LaSalle 1995; Streever and Crisman 1993; Simenstad et al 1993; Burney et al 1989; Evans 1989; Roberts 1989; Cammen et al 1976; Delphey 1991). The time frame for this community development varies greatly by habitat type and the complexity of the community and the trophic level examined. In some studies, substantial similarity in experimental site and natural reference site communities was noted within as little as 6 months. At other sites, communities were not deemed equivalent even after 10-15 years. Natural species composition and community structure of zooplankton and aquatic invertebrates appears to develop more rapidly than higher trophic levels.

   A period of community evolution should be expected, as physical conditions and vegetative communities take some time to develop. The initial colonizers take advantage of disturbed conditions; as the community matures, these colonizers may be displaced by other species. For example, Collins et al (1990) and Bailey-Brock (1989) note shifts in dominant species on reefs. Niesen and Lyke (1981), Levings and MacDonald (1991), Simenstad and Thom (1996), and Moy and Levin (1991) note similar shifts in community composition and structure in tidal marshes.

2. Were abundance, biomass, or density of resident species equal to or greater than that at reference habitats?

These data would suggest a successful restoration effort, and a potential for population benefits.

As Table 4 indicates, abundance, density, and biomass were greater than at the reference habitat at some rehabilitated sites, and lower at others (Chamberlain and Barnhart 1993; Dibble et al 1995; Morrow et al 1995; LaSalle 1995; Streever and Crisman 1993; Simenstad et al 1993; Fell et al 1991; Landin et al 1989; Havens et al 1995). Where the techniques of restoration are well established, as for trout and other salmonids, biomass increases were often documented (Gore 1985; Gourley and Lillquist 1993; Hunt 1988; Carline and Klosiewski 1985; Shields et al 1993; Moore and Gregory 1988). But for seagrasses and salt water communities, natural habitats often were more productive, at least during the short-term of monitoring following most projects (Sacco et al 1994; Ecoshore, Inc. 1992). Bombace et al (1994) also report an increase in biomass of sessile species such as mussels on artificial reef habitat and suggest that the reefs therefore may support greater fish populations. Biomass of benthic invertebrates on an artificial reef in Delaware Bay was almost three orders of magnitude greater than that of the surrounding mud flats (Foster et al 1994).

3. Was there evidence of reduced disease incidence?

Reduced disease incidence would indicate lower stress on populations and a potential for reduced mortality.

Disease incidence was not routinely measured following physical habitat restoration. Reduced disease incidence is reported following reduction of pollution levels (Sparks 1992), but this was an incidental observation.

4. Did sustainable, improved, fisheries result?

A sustained increase in the number of harvested fish, not supplemented by hatchery stocking, suggests that the rehabilitated habitat is supporting enhanced reproduction, enhanced growth, and/or reduced mortality, all of which point to population-level effects.

Wetland restoration efforts to date have generally been too small to result in increases in general fisheries. Nevertheless, sustainable fisheries have been documented to result from restoration projects, primarily in small river and stream systems where restoration work is of a scale to affect an entire reach of river/stream (Sparks 1992; Gourley and Lillquist 1993; Stuber 1985). Several large-scale reef restoration projects in Italy, however, document restoration of nearshore sport fisheries following placement of artificial block reef complexes (Relini and Orsi Relini, 1989). Analysis of octopus catch on artificial reefs in Japan (Polovina and Sakai 1989) suggests increases in catch resulting from artificial reef placement.

An indirect indication of populations capable of sustaining significant take is provided by observations of increased use of rehabilitated habitat by wading birds and shore birds, who feed on invertebrates and small fish (Wilcox 1986. Continued use by such birds suggests a sustainable population of fish available to these predators.

5. Was there evidence of spawning, egg/larval development, foraging, use by a key life-history stage, and/or long-term residence?

If a rehabilitated habitat provides these benefits to a species, it can be said to enhance the range and viability of the species.

Many authors noted evidence of spawning, foraging, reproductive success, and use of habitat by migrating juveniles (Novick and Hein 1982; Morrow et al 1995). Lindberg and Marzuola (1993) identified the first known delta smelt spawning habitat at the Cache Slough restoration site in the Bay-Delta in 1993. Successful reproduction in rehabilitated habitat is specifically noted by Weller (1995) and Fago (1977). Many, including England et al (1990); Shreffler et al (1992), and Miller (1993) note use of rehabilitated freshwater and estuarine marshes by outmigrating salmon smolts. Bassett (1994) reports increased populations of walleye and smallmouth bass as a result of improved spawning habitat. Indirect evidence of successful use of habitat is, of course, provided by the permanent occupation of rehabilitated habitat by diverse assemblages of species.

In California, total production at the Torey Pines Artificial Reef was determined to be 9 times the production of adjacent habitat (Johnson et al 1994).

6. Was there direct and indirect evidence of reduced mortality?

Evidence that mortality at any life history stage from any source is lower following restoration would indicate a potential for a population-level effect, although adult population growth is the best indicator of this.

Bell (1993) discusses the potential that predation may be lower in rehabilitated marshes, although this hypothesized failure of predators to utilize rehabilitated areas early in their development could account for many of the observed differences in fish and wildlife assemblages. Caddy and Stamatopoulos (1990) suggest that disproportional limits in shelter of various sizes may constrain recruitment by exposing one or another life history stage of a species to increased predation when it reaches the size at which shelter is limited.

There were many studies with indirect evidence of reduced mortality, particularly at early life-history stages. Increases in salmon smolt production in rehabilitated streams, increases in the number of trout within a stream reach, and changes in the age-class structure of populations were all noted (Gore 1985; Gourley and Lillquist 1993).

Applications to the Bay-Delta

If the distribution and scope of habitat restoration in the Bay-Delta is adequate and based on an understanding of the needed physical structure and ecosystem functions, restoration could provide significant benefits to both anadromous and resident species.

E. Potential Incidental Benefits

No systematic search for evidence of incidental benefits of restoration to people was made. A few interesting incidental benefits were noted, however.

1. Dredge Spoil Disposal

Habitat restoration appears to be quite successful on dredge spoil which has been properly placed and protected from erosion (Cammen et al 1976). Disposal of clean dredge spoil may therefore be considered a potential element of a proactive habitat restoration effort. This has already been demonstrated in the Bay-Delta for USACE dredge disposal at Donlon and Venice Cut Islands (England et al (1990), and throughout the United States (LaSalle et al 1991; Packard and Kent 1976; Newling and Landin 1985; Landin et al 1989).

2. Water Quality Enhancement

Rehabilitated marsh habitat has been shown to effectively remove nutrients and organic carbon from agricultural and urban runoff, and from municipal effluents and some industrial wastes (Kadlec and Knight 1996; McArthur 1989; Knight and Ferda 1989; Maristany and Bartel 1989; Kleiss et al 1989; and Palmer and Hunt

1989). Marshes may transfer organic carbon and other nutrients from the water column to below-ground, with this transfer mediated by bacterial breakdown of complex molecules into nutrients useable by aquatic and emergent vegetation. The ability of marshes to transform/fix nutrients in the water column varies by season, temperature, depth, marsh vegetation type, residence time, and nutrient mix.

3. Flood Control

Several studies indicate channel deepening, and increases in channel capacity, as a result of restoration of riparian habitat along river banks (Friberg et al 1994; Berger, 1992), particularly where activities such as grazing have affected the natural stream-bank structure. Meander corridors, which result in reduced flow velocities and overbank flow resulting in short-term flood flow storage, are currently being considered as features of long-term flood control plans in the Sacramento Valley (USACE 1994).

4. Waste Disposal

Collins et al (1994) discuss the potential to convert many industrial wastes to physically and chemically stable blocks which can be used for artificial reefs, and there have been many experiments using concrete rubble, tires, and old automobiles as base materials for reefs.

SUCCESS AND FACTORS AFFECTING SUCCESS

A. Success/Failure Definitions

Most habitat restoration has been mitigation for project impacts to areas of natural habitat. In this context, success has most often been defined as creation of structurally, functionally, and biologically equivalent conditions at the restoration site (Josselyn et al 1990). Much of the prevailing disappointment over the results of habitat restoration efforts is rooted in the goal for the rehabilitated habitat: to exactly match the impact site, acre for acre, species for species.

From our review, it is quite clear that exact matches at all levels are difficult to accomplish, particularly in the early stages of development of a rehabilitated area and particularly for small plots which are different in structure and relationship to the overall ecosystem than the natural habitats they were intended to replace.

At the ecosystem level, success need not be defined in such narrow terms. At this scale, success may be defined as:

1) The establishment of critical ecosystem functions, such as hydrodynamics, physical habitat structure, interconnectedness of habitats, water chemistry, nutrient cycling, sediment transport and deposition, overbank flow, and the like;

2) The establishment *conditions and functions* suitable for a wide range of native species, including but not limited to: shelter, spawning habitat, nurseries, foraging opportunities, and protection from the impacts of pollutants, water diversions, and excessive harvest; and

3) The development of a functioning biological community at a site which includes native species in an assemblage resembling that of natural habitats of the same type and general location.

Given this working definition, it is clear that many habitat restoration projects have been "successful," even if they have not accomplished the exact 1:1 match desired for mitigation. Many studies concluded that rehabilitated communities were quite similar to natural reference communities in diversity and function, but with less dense, abundant, or well-distributed populations of target species. A larger scale and a better integration of restoration efforts into the overall ecosystem should be considered in mitigation efforts (Josselyn et al 1990).

B. Factors Affecting Success

The factors which affect the structural, functional, and biological integrity and therefore "success" of restoration efforts are discussed routinely in the literature, both in general terms and in terms of specific case studies. Factors most commonly identified include:

1. Location

   The site should provide appropriate physical and hydrodynamic conditions for the community desired, including isolation from impacts of urban uses. In reviewing 40 wetland mitigation projects in Florida, Erwin (1991) found that 58 percent were located where surrounding land uses prevented the wetlands from providing the intended functional values.

2. Appropriate Hydrologic Conditions

   Proper water levels, hydroperiod, drainage patterns, and natural hydrologic connection are essential for successful wetlands projects. In reviews of restoration projects, Erwin (1991), Crewz (1992), and Lewis et al (1990) found that hydrologic problems were the most frequent cause of restoration failure.

3. Slope and elevation/depth

   Numerous researchers noted differences in the natural versus rehabilitated habitat related to slope and/or elevation/depth. These features of a site govern the velocity of flow, wave force distribution, erosion potential, residence time for inundated areas, and other factors which affect the physical stability and function of a site.

4. Substrate

   The chemical and physical properties of the soil, including grain size, organic carbon, and nutrient content can be critical to the establishment, or the rate of establishment, of vegetative communities. These factors may influence the development of biological communities.

5. Protection from stressors such as wave forces, flood flows, toxics, etc.

   Knutson and Steele (1988) determined the maximum wave fetch for stable dredge spoil placement and marsh planting (< 3.0 km), unless a more intensive program of maintenance planting is pursued. Fetch of greater than 9.0 km was found to be unsuitable for rehabilitated wetlands. Many rehabilitated wetlands receive direct discharge from parking lots, industrial sites, and urban areas which could lead to long-term water quality problems (Erwin 1991).

Sparks (1992) noted that waves from boat wakes, and turbulence from propeller wash may make it difficult for submerged aquatic vegetation to become established.

Kusler and Kentula (1990) also point out that toxics, groundwater pumping, vehicle use, sedimentation, and a myriad of other human disturbances can cause rehabilitated areas to fail.

6. Salinity

Conversion of hypersaline areas, such as salt ponds and brackish marshes, to tidal marsh may be hindered by the inability of typical intertidal species to adapt to saline conditions.

7. Disconnected Habitats

There is an extensive literature, not specifically reviewed in this report, related to the difficulties involved in establishing functioning habitats which are small and/or isolated. Such habitats may not have the capacity to support viable populations.

8. Exotic species

Exotic species may compete directly, or prey upon, native species, affecting their ability to maintain viable populations. Exotics may also interrupt essential biological mechanisms, such as nutrient cycling, which can change species composition and create "un-natural" community development (Zedler 1992). The restoration process itself may involve removal of vegetation, creating barren areas and opening habitat to invasions of opportunistic exotics. Exotics species invasions are also frequently a result of hydrologic problems (Erwin 1991; Crewz 1992) and many restoration projects involve reestablishment of hydrologic regimes which may enhance the potential for development of a native wetland community.

9. Stocking/Seeding

Many of the studies reviewed documented failure of stocking, seeding, and planting programs, due to planting at improper elevations and densities, failure to perform follow-up planting, and use of the wrong species (Erwin 1991). These failures are sometimes followed by a successful colonization by natural means. Natural colonization occurs when and where physical, hydrodynamic, and biochemical conditions are appropriate for the colonizing species. Artificial propagation may fail because these conditions are not appropriate.

10. Implementation Problems

In sites where construction is significant, failure to carry out the restoration plan may result in many of the above problems. Morrison et al (1994) point out that even small variations in vegetative community, which may result from minor differences in implementation of a restoration plan, can favor one suite of wildlife species over another.

In highly engineered projects, implementation errors may cause problems such as depths which vary significantly from design parameters (Jensen et al 1987).

11. Use of commercial "cultivars"

If planting is undertaken, native species, from the immediate vicinity of the restoration project, should if feasible be used to avoid genetic problems and to provide the best chance of successful "take." Native species may have highly specific habitat requirements, and therefore play a very different role in the ecosystem than non-native species of the same genera. Callaway and Josselyn (1992) note such differences for native and introduced cordgrass in San Francisco Bay (*Spartina foliosa* and *S. alterniflora*, respectively).

12. Ability to manage adaptively

Human understanding of restoration is limited, and a systematic monitoring and adaptive management program is necessary so that inadvertent mistakes in design and implementation can be corrected as time passes. This has seldom been feasible, because of funding limitations.

13. Scale

A majority of habitat restoration has been small-scale, less than 100 hectares. Because of their relatively low area to edge ratio, small areas of isolated habitat are more subject to disturbance effects than large areas and they seldom provide for all of the key physical structure, hydrologic and chemical functions, and biological complexity of natural habitats. Small scale also limits the potential for significant population-level effects.

14. Lack of understanding of the functional requirements of the ecosystem.

In their review of wetlands creation in the western United States, Josselyn et al (1990) suggest that a thorough knowledge of the physical structure, hydrologic and chemical functions, and biological functions which may affect success must be developed before restoration is attempted. Their list of factors:

a. Site history, including past habitats and disturbance events
b. Topography
c. Water control structures and their operation
d. Hydrology
e. Flood events
f. Sediment budget
g. Soil suitability for supporting the proposed habitat
h. Existing vegetation
i. Existing wildlife
j. Adjacent site conditions

Others, such as Bacchus (1991) discuss these factors as critical to success. To this list, Gore et al (1995) would add water quality. Zedler (1995) would further add:

a. A regional perspective
b. Rare and endangered species requirements

In addition, our review of cases would add:

a. The timing of restoration actions -- season, tidal stage, hydrologic year-type, etc.
b. Specific handling practices for plant and animal species

In sum, it is critically important to review the literature related to conditions at the proposed restoration site and related to other efforts to accomplish similar restoration goals to determine what has worked previously. Review of specific techniques used to obtain reported effects is especially important.

THE RESTORATION PLANNING PROCESS

Scale and Process

Restoration planning has historically been quite focused -- a nearby mitigation site is selected for restoration and a plan is drawn up to manipulate physical structure, restore some form of hydrologic regime, plant or seed the area, and monitor for a brief period. The goal has been to re-create conditions at the mitigation site which occur at the impact site. This "in-kind" approach has led to single-species and single-habitat restoration efforts, often resulting in small-scale, isolated habitats of little value, referred to as "band-aids" (McIntosh et al 1994).

In the last 10 years, disappointment with the limited results of this approach has begun to drive "restoration biologists" to take a more regional, ecosystem-oriented approach. The State of California's Natural Communities Conservation Planning process (NCCP) is an example. The South Florida Water Management District's efforts on the Kissimmee River is another.

California's NCCP process for such regional efforts is an example of the shift in focus from band-aid-scale work to ecosystem-scale work. Putting aside the NCCP's administrative structure, the fundamentals of this process are:

1) A focus on a combination of protection and restoration efforts

   The NCCP process begins with an inventory of existing habitats, which are then prioritized for protection.

2) Regional-level study

   A consortium of scientists is then convened to conduct studies of regional ecosystems -- the distribution of habitats and how distribution may be influenced by soils, groundwater, surface water hydrology, disturbances such as fire and drought, and so forth. When these underlying forces are understood, it is then appropriate to develop regional plans.

3) Development of general regional plans

   General goals and objectives, which are based on an understanding of key ecosystem functions, are formulated. The plans are phased to reflect the need to implement critical elements first.

4) Simultaneous implementation and testing

Efforts to protect existing habitats, and to rehabilitate habitats where there is good understanding of the restoration goals, objectives, and methods, then proceed in parallel with experiments in restoration designed to answer questions about effectiveness, technique, scale, etc.

Such large-scale experiments were also conducted on Florida's Kissimmee River to determine the feasibility of restoring key habitat functions prior to a full-scale, ecosystem-level restoration processes (Toth 1993).

To avoid the piecemeal approach which many now believe to contribute to failures (Zedler 1995), restoration planning therefore may begin with a study of the structure and function of the ecosystem. Goals and objectives should be based on this understanding of ecosystem function, and plans should be designed to be compatible with it.

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CONCLUSIONS AND APPLICATION TO THE BAY-DELTA ECOSYSTEM

A. Conclusions

1. Habitat restoration has the capacity to provide significant fish and wildlife benefits.

Given the preponderance of small-scale and narrowly focused restoration efforts conducted to date, there have been a surprising number of successes. Most restoration efforts have provided significant fish and wildlife benefits, even if they have not produced functionally and biologically equivalent habitat to the reference habitats. Virtually every report reviewed notes some level of success -- restoration of functions, initial development of a viable vegetative community, and colonization and use by fish and wildlife.

Although habitat restoration efforts are criticized, this criticism is most often related to the inability of rehabilitated habitat to fully offset losses of similar natural habitat on a 1:1 basis, particularly in the short-term. In short, when natural habitat is destroyed by a project, replacement habitat may not fully mitigate for the loss until well after the loss has occurred. For a number of reasons, there is also uncertainty that the rehabilitated habitat will, in fact, fully mitigate for loss of the impacted habitat. Subtle differences in land form, substrate, hydrology, and other factors may result in a mitigation site which resembles the natural site in some aspects but is not identical to the impacted site. Most criticism of habitat restoration is therefore based on the inability of restoration to *exactly duplicate* the conditions and biological community of the impact site.

As Streever and Crisman (1992) point out, there is significant intra-wetland and inter-wetland variability, even among natural wetlands of the same type. It may therefore be unrealistic to expect rehabilitated habitats to exactly duplicate impacted areas.

However, even long-time critics of habitat restoration (Zedler and Langis 1991) note that rehabilitated habitats perform many of the functions and have many of the benefits of natural habitats. With the caveat that *exact duplication* of a particular natural habitat at a given site is probably an unrealistic goal, we can conclude:

a. Restoration of habitat or ecosystem functions is feasible.

b. Restoration of plant communities is often successful. Vegetation virtually always colonizes the rehabilitated site. Plant communities generally evolve to resemble natural reference communities. Failures are readily explained on the basis of factors such as inappropriate depth, soils, and hydrologic regimes.

c. Restoration of animal communities is also often successful; fish and wildlife virtually always use the rehabilitated habitat. Communities of animals have been shown to evolve to resemble natural reference communities.

d. There are some reports of incidental water quality and flood control benefits.

Given an ecosystem-level approach to restoration, which emphasizes restoration of habitat diversity/complexity and broad distribution of habitats throughout the ecosystem, exact duplication of an impacted habitat may cease to be a significant issue.

2. **The relative success of habitat restoration efforts depends largely upon proper design and execution of a restoration plan.**

There are examples in the literature of complete failure -- habitat eroded by flood flows, plants and wildlife which do not colonize as expected, problems associated with exotic invasions. Most of these failures are readily explained by some error in design or implementation.

There are no guarantees that restoration will work at every site and under every condition. Restoration with a narrow focus on a single species or habitat variable has a higher chance of failure than restoration aimed at a broad suite of the physical, functional, and biological features of a habitat type. Landscape-scale restoration which deals with multiple habitats and their interaction may have a better chance of success. Success is more likely if restoration addresses the full range of factors influencing biological community viability -- from physical habitat to water chemistry to the impacts of human activities.

Regardless of scale, however, there is reasonable assurance that well-designed and well-implemented restoration efforts will provide significant benefits to plant and animal communities.

3. **Increases in the abundances of localized populations are well documented; however population gains at larger spatial scales are less well defined.**

   There are a number of reasons for the failure to demonstrate population-wide responses:

   a. Monitoring has generally been inadequate to rule out redistribution. However, there are strong ecological indications that colonization eventually results in functionally "new" populations of many species.

   b. In most cases, pre-project and post-project monitoring has not been adequate in scope to permit conclusions about population-wide responses.

   c. Monitoring virtually never addresses the potential for other factors to affect populations. For example, restoration of spawning habitat for salmon may be readily offset by increased harvest, increased predation, changes in ocean conditions, changes in in-stream flow regimes (either natural or human-induced), etc.

   d. The scale of most restoration efforts has been too small to have population-wide effects.

4. **Restoration has a greater likelihood of success if it is holistic in scope; i.e., based on an analysis of physical structure, hydrologic functions, soil and water chemistry, and biological conditions at both the restoration site and within the ecosystem (Garlo 1992).**

B. Application to the Bay-Delta Ecosystem

1. Habitat restoration in the Bay-Delta is being proposed as a long-term, proactive effort to reestablish the *conditions and ecological functions* necessary for native species and other species of concern to maintain viable populations. Because the purpose is not to mitigate for the loss of a specific habitat type and biotic community, the problems associated with *mitigation* projects triggered by a specific project impact do not necessarily apply to this effort.

   Without the requirement to exactly duplicate a specific impacted habitat, the Bay-Delta restoration effort can be focused on reestablishment of the structure and function of the ecosystem, and on restoration of many habitat types throughout the ecosystem. In short, the current CALFED-led effort is an almost unique opportunity to approach habitat restoration from a regional, ecosystem perspective rather than from the often-criticized site-specific, single-species perspective.

2. A system-wide habitat restoration effort in the Bay-Delta would very likely have significant benefits for the biological community, including native species of concern.

3. Such an habitat restoration effort should address the full range of physical, hydrologic, water quality, biological, and human-induced factors which control the conditions in which Bay-Delta organisms live.

4. The scope of this habitat restoration should be adequate to ensure conditions needed for survival of communities and target species throughout their range and under a wide range of conditions.

5. Habitat restoration should be based on a thorough, multi-disciplinary, evaluation of the ecology of the Bay-Delta system .

6. The restoration program should be comprehensive in geographic scope, but flexible in approach. Initial restoration efforts should be widely dispersed and adequate in scope to provide meaningful tests of restoration success. Monitoring should be adequate to permit the benefits of the restoration efforts to be assessed, and to give insight into potential improvements for later efforts.

7. Adaptive management should be a feature of the restoration plan but it may not be practical to await scientific certainty before adaptively managing. Many researchers note that pursuing habitat restoration at a landscape scale may be a prerequisite for success, because small "test" efforts may not provide the diversity of functions needed for functioning systems and communities to be established. They also note that the desired effects of restoration may not be realized for many years. Implementing an adequate-scale restoration plan should not be delayed pending results of small tests.

   Therefore, a commitment to adaptive management should not imply that implementation of major program elements will be deferred until we have greater scientific certainty about their results. Further, it is also probably advisable to initiate early adaptive management based on monitoring of ecological functions, rather than awaiting data about long-term population trends, which can be obscured by year-to-year variation.

   In planning for adaptive management, it will be useful to recognize the "feedback" between restoration efforts and fish and wildlife populations. As Garlo (1992)

> notes, fish and wildlife alter habitat in which they exist in a number of ways and can be major factors influencing vegetation (and in some systems) hydrology.

Finally, we would make an observation about restoration methods for the Bay-Delta. The literature is rife with examples of highly engineered projects which have been re-shaped by unanticipated natural forces -- from engineered islands which have been re-contoured by flood flows (Landin et al 1989) to carefully planted reefs and seagrass beds which washed away from wave action only to be recolonized naturally (Fonseca et al 1990). Numerous authors note that the reestablishment of "natural" structure and function is often followed by rapid natural plant and animal colonization. As LaGrange and Dinsmore (1989) note:

> "Planting seeds or propagules and stocking animals seems unnecessary to restore drained wetlands. Once water is added to the [previously] drained basins, wetland plant seeds germinate, and the site is quickly colonized by a representative community of wetland animals. Restorations of this type are an easy and cost-effective way to add wetlands to an existing complex or to create new wetlands in areas where all have been drained."

There are similar experiences in the Bay-Delta, including those at Donlon and Venice Cut islands (England et al 1990) and at The Nature Conservancy Cosumnes River preserve, where cottonwood-willow riparian vegetation naturally regenerated on spoil left following a levee break (R. Reiner, personal communication).

Although there will be a necessity to carefully engineer some elements of a comprehensive habitat restoration program for the Bay-Delta, we may have more long-term success by re-establishing natural processes. Such a balanced approach is proposed, for example, for reestablishing a meander zone on the Sacramento River (USACE 1994). The Corps proposes to:

> ". . . incorporate the concept of a meander zone based on historic river migration paths as well as a continuous riparian corridor along the Sacramento River. The geomorphic and hydrologic characteristics of the river system will dictate which features would be appropriate for implementation; however, existing facilities related to flood control features, transportation routes, urban development, and environmental resources would also be considered."

Rather than attempt to create a static system with precisely defined characteristics, the Corps further proposes:

". . . channel migration would be allowed to continue within purchased easements, except where flood relief structures, flood control system operation, or public structures are threatened. . ."

Such an approach, allowing (to the extent feasible) natural processes to shape the land in a manner which will promote change and habitat diversity, would be consistent with both the theoretical considerations explored in Part 1 of this report and the reported results of many case studies. Provided that the initial plan for ecosystem restoration adequately provides for a variety of habitats, well-distributed throughout the system, a dynamic and largely self-sustaining restoration program will be feasible, and will provide an appropriate range of aquatic, riparian, and upland habitats in the Bay-Delta and its upstream tributary ecosystem.

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Table 1. Literature Review Team Organization

Subject	Reviewers	Reviewer Affiliation
Chairman	Peter Rhoads	Metropolitan Water District of Southern California (MWDSC)
Foundations and Principles	William Alevizon (Author, Part 1)	The Bay Institute
The Rehabilitation Planning Process	Charles Hanson	State Water Contractors
Wetlands Case Studies	Phyllis Fox and Jud Monroe (Authors, Part 2)	Consultants, MWDSC
Salmonid Case Studies	Randy Bailey	Consultant, MWDSC
Lake and River Case Studies	Karen Levy and Rod Fujita	Environmental Defense Fund
Reef Case Studies	Jud Monroe	Consultant, MWDSC
River Case Studies	Robert Nuzum	East Bay Municipal Utility District (EBMUD)

Table 2. Habitat and Ecosystem Functions Restored in Documented Habitat Rehabilitation Efforts

Habitat Function Restored	Location and Project Description	Reference
Normal Temperature Regimes	Flaming Gorge Dam; modified penstocks restored temperatures below the dam outlet.	Holden and Crist 1981
	Peanut Lake, FL; temperature and salinity regimes restored in a lake dredged to restore tidal flushing.	Motta 1995
Increase Physical Habitat Diversity	Melk River, Austria; channelized river was allowed to meander.	Jungwirth et al 1993
	Mink Creek/Pine River, Canada; meanders were encouraged in a previously channelized river; greater bed stability resulted.	Newbury and Gaboury 1993
	River Gelsa, Denmark; meanders recreated; riffles and pools reestablished in channelized river.	Friberg et al 1994
	Hotophia Creek, Mississippi; pool habitat and riffle velocity was increased.	Shields, Cooper, and Knight 1993
	Sevier River, Utah; incised channel restored as grazing is removed to reduce channel bank damage.	Gourley and Lillquist 1993
	Un-named stream in Quebec; riffle-pool ratio restored with rock dams and deflectors.	Gore 1985
	Wisconsin; riffle-pool-glide sequences improved; some pools deeper.	Lyons and Courtney 1990

Habitat Function Restored	Location and Project Description	Reference
	James River, VA; highly varied island and marsh habitat complex created in main channel area.	Landin and Newling 1988
	Sheep Creek, Colorado; river channel structure stabilized by eliminating cattle grazing.	Stuber 1985
	San Joaquin River, CA; dredge spoil used to restore shallow-water habitat structure.	England et al 1990
	Middle Crow Creek, Wyoming; river channel structure was restored through flow augmentation.	Henszey et al 1994(a)
	Upper Mississippi River; dredge and spoil process used to create island, shallows, deep-water complex.	Soballe and Gaugush 1994
	Norway; habitat diversity restored with rock islands in a channel.	Brittain et al 1993
	Wisconsin, various locations; stream channels made more natural and diverse in structure through narrowing channel width.	Hunt 1988
	Camp and Bear Creek, Oregon; removal of grazing resulted in improved hydraulics and gravel movement.	Hunter 1991
	South Platte River, Colorado; pools and riffles restored and water velocities decreased to approximate pre-channelization conditions.	Stuber 1984

Habitat Function Restored	Location and Project Description	Reference
	Vincent Creek, Coos Bay, Oregon; pools of varying geometry and depth.	Anderson and Miyajama 1975
Reductions in Toxics from Mine/Agricultural Discharges	Potomac River; small reservoir buffered mine discharges -- improved downstream water quality	Diamond et al 1993
	Lower Oconto River, Wisconsin; water quality and sediment characteristics changed with closing of pulp mill.	Rost et al 1989
	Southwest Virginia; FAILURE; terrestrial reclamation of strip mine areas failed to enhance recovery of headwater streams.	Matter and Ney 1981
Rehabilitation of Water Quality	Strawberry Creek, Berkeley, CA; turbidity, suspended sediment, nutrient load, and bacterial concentrations reduced following physical rehabilitation.	Charbonneau and Resh 1992
	Louisiana Bottomland Hardwood Systems; rehabilitation of flooding patterns reduced turbidities to high-normal range.	Ewing 1991
	Indian River, FL; water quality in a previously impounded area was restored to levels approximating outside areas.	Ecoshore, Inc. 1992
	Port of Long Beach, CA; water quality in a restored marsh was equivalent to a natural marsh, except for temperature and clarity, due to restricted tidal exchange.	MEC Analytical Systems 1995
	Lake Shenipsit, Connecticut; clarity restored through an aeration project; shift from anaerobic to aerobic regime.	Kortmann et al 1994

Habitat Function Restored	Location and Project Description	Reference
	Medical Lake, WA; aluminum sulfate applied to reduce phosphorus cycling resulted in restored water clarity and productivity.	Soltero et al 1981
	Lake Puckaway, WI; water clarity restored as a result of carp control and re-planting regime.	Congdon 1993
Rehabilitation of Tidal Influence	Cache Slough, California; shallow-water habitat restored with tidal exchange in former agricultural fields.	Lindberg and Marzuola 1993
	Humboldt Bay, CA; salt marsh functions, including variable salinity, restored by breaching dike.	Chamberlain and Barnhart 1993
	Bolsa Chica, CA; tidal influences and processes restored in 150-acre marsh.	Novick and Hein 1982
	East-Central Florida; tidal regimes were restored to a diked marsh; estuarine salinities and dissolved oxygen levels were restored.	Rey et al 1990
	Pine Creek, Connecticut; marsh diked for 400 years was restored, with tidal flushing and sediment scour in lower (adjacent creek channel); brackish water quality improved.	Steinke 1986
	Tampa Bay, FL; tidal flushing restored in isolated mangrove-rimmed embayment.	Kurz et al 1995
Rehabilitation of Sediment Regimes/Organic Accretion	Burlington, NJ; restored tidal influence resulted in rehabilitation of natural accretion of sediments to the marsh area at a rate of 0.3 to 8 cm/year.	Caiazza 1989

Habitat Function Restored	Location and Project Description	Reference
	Indian River, FL; *Spartina* marsh restored, with subsequent increases in organic content of soils.	Banner 1977
	Lake Peoria, Illinois; backwater lakes were planted and protected, which increased entrapment of nutrient-rich sediments in marshes and reduced sedimentation of deeper river areas.	Roseboom et al 1989
	North Carolina, various; dredge spoil stabilized through planting dredge spoil.	Cammen 1976
	Lake Springfield, Illinois; lake sedimentation from runoff controlled, with dredge spoil returned to topsoil to agricultural areas.	Buckler et al 1988
	Intracoastal waterway, Georgia; salt marsh restored on dredge spoil. Organic soils building following restoration.	Cole 1978
	Queen Charlotte Island area; gabion placement restored stable gravel deposition.	Klassen and Northcote 1988
Rehabilitation of Nutrient Cycling	Landfill in the Puyallup River, WA; the restored wetland produced nitrites and TOC; was a sink for nitrates.	Brostoff and Clarke 1992
Rehabilitation of Groundwater Levels	Maine; improved total exchange resulted in improved groundwater levels and soil salinity.	Dionne et al 1994
	Fort Lauderdale, FL; water levels raised following rehydration of periodically flooded wetland.	Weller 1995

Habitat Function Restored	Location and Project Description	Reference
Rehabilitation of Estuarine and Intertidal Functions	Grays Harbour, WA; oyster-shell reefs were restored, with 75% integrity following three years.	Dumbauld et al 1993
	San Diego Bay, CA; soils for cordgrass beds were supplemented	Joy Zedler in Thayer 1992
	Fraser River, BC; water clarity and channel structure restored in marshes on lower Fraser.	FREMP 1995
	Chesapeake Bay, MD; stable marshes created in low-wave energy areas.	Knutson and Steele 1988
	Tacoma, WA; landfill was rehabilitated to a functioning marsh, with natural topography, soils, and water chemistry.	Simenstad and Thom 1996
	Chehalis River, WA; DO, temperature, and salinity regimes were restored in a created estuarine slough.	Simenstad et al 1992
	Upper Newport Bay, CA; salt ponds were converted to physically diverse habitats with a range of soil conditions.	Wilcox 1986
	Hayward, CA; sediment characteristics similar to natural reference marsh were restored in abandoned salt ponds.	Niesen and Josselyn 1981

Habitat Function Restored	Location and Project Description	Reference
	Mangrove-Rimmed Habitats, various; rehabilitation of tidal influence altered the deposition of organics in mangrove- rimmed marshlands.	Vose and Bell, 1994
	Puget Sound, WA; rehabilitation of tidal influence created a mudflat/emergent wetland/tidal channel complex.	Shreffler, Simenstad, and Thom 1992
	Sun City, FL; flood control project modification. Hydroperiod of cypress swamp restored.	Devroy and Hanners 1988
Rehabilitation of Reef Structure	Pendleton Artificial Reef, CA; Diablo Canyon, CA; stable reef structures have been in place for over 10 years.	Schiel and Foster 1992
	Poole Bay, England; coal/ash blocks provided a stable reef structure.	Collins et al 1990
	Reef experiments in Australia; many cases cited of long-term artificial reef stability.	Pollard 1989
	Rhode Island; shelter for lobsters restored artificially.	Sheehy and Vik 1992
Rehabilitation of Riverine Hydrologic Regimes	Blanco River, Colorado; stable, sinuous channel, with seasonally flooded plain was re-established in previously channelized river.	Berger 1992
	Blue River, Colorado; stable channel and floodplain re-established in area of mine slag.	Fullerton and Long 1989

Habitat Function Restored	Location and Project Description	Reference
Wetland/Dune Interface Restored	Gateway National Park, NY City; dunes recontoured and wetland dredged to restore natural physical habitat diversity.	Cook and Tancredi 1990
Rehabilitation of Vernal Pool Hydrology/Structure	Santa Barbara, CA; vernal pool structure recreated in upland habitat; flooding durations restored.	Pritchett 1990
Reductions in Toxics and Turbidity	Illinois River, Illinois; pollution control reduces algal blooms and turbidity; toxics levels reduced.	Sparks 1992
Rehabilitation of Sediment Trapping	Intercoastal Waterway, GA; dredged material disposal area re-graded and planted to restore marsh; natural siltation and soil building were restored.	Reimold et al 1978

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Table 3. Plant Community Development in Habitat Rehabilitation Projects

Habitat Type	Proj. Location and Description	Monitoring Period	Results	Reference
Wetlands	Donlon Island and Venice Cut Island, CA; restore tidal marsh using dredge spoils.	1987-1989	Tules well-developed in 1st year; Riparian and tidal herbaceous in 2nd year.	England et al 1990
	Burlington County, NJ; restore freshwater tidal marsh.	1986-1987	Upland and wetland communities developed. Community dominated by planted and volunteer species.	Caiazza 1989
	Puyallup River, WA; convert landfill to marsh/wetland.	Five years	Naturally colonized by cattails, bullrush, and other estuarine plants. 57 plant species by year 5.	Brostoff and Clarke 1992
	Humboldt Bay, CA; convert sawmill log pond to tidal marsh.	1981-1982	Cordgrass, pickelweed and other marsh species increased; other species decreased.	Chamberlain and Barnhart 1993
	Maine; natural hydrology was restored to impounded and dredge-spoil marshes.	Five years	Salt marsh plants restored (personal communication).	Dionne et al 1994
	Stonington, Connecticut; restore tidal flushing to an impounded brackish marsh.	13 years following rehab	Tidal marsh plants had largely replaced *Typha* and had colonized unvegetated areas.	Peck et al 1994

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Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Florida, various locations. Compares 22 restored coastal marshes to 6 natural marshes.	1-10 years after rehab	Little difference was found between created and natural marshes, either in dominant species, total cover, and below-ground biomass.	Roberts 1991
	South Carolina; convert abandoned soil borrow pit to forested wetland.	1992-1993	Alluvial swamp forest species successfully established; percent cover increased 92-93.	McCuskey et al 1994
	Pointe Mouillee, Mich.; barrier island built with dredge spoil to protect restored marsh area.	1993-1994	Aquatic plant community was similar on restored marsh and natural marsh, but lower density.	Dibble, Hoover, and Landin 1995
	Conesus Lake, NY; ponds created adjacent to river inlet.	1992-1994	Planted reed grasses established in 3 of 4 wetland ponds.	Morrow et al 1995
	Texas, various locations; *Spartina* marshes restored along coast.	Spring 1986, 2-5 years after rehab	Plant densities and above-ground biomass in rehab. marshes were higher than in natural reference marshes.	Minello and Zimmerman 1992
	Winyah Bay, SC; *Spartina* marsh established with dredge spoil adjacent to mainstem channel.	4-8 years after rehab	Younger site had taller plants and more above-ground biomass; older site had greater stem density and below-ground and total biomass. This suggests successional processes leading to a natural marsh condition.	LaSalle et al 1991

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Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Pascagoula, Miss.; upland converted to an intertidal marsh through excavation.	1992-1993, 7 years after rehab	Constructed marsh had similar community to reference natural marsh, but generally less root-zone biomass.	LaSalle 1995
	Tacoma, WA; landfill converted to marsh along river.	7 years	56 vascular plants have colonized the intertidal area; vegetation shift from intertidal sedge and bare mudflats to complex community.	Simenstad and Thom 1996
	Chehalis River, WA; estuarine slough created in river delta.	1-time comparison with natural marsh	Created slough naturally colonized by brackish and freshwater marsh vegetation; above-ground vegetation biomass was 5 times higher in the natural slough. Below-ground biomass higher in natural slough.	Simenstad et al 1992 Simenstad et al 1993
	San Diego Bay, CA; intertidal salt marsh constructed on upland habitat.	1989-1990, 4-5 years after rehab	Natural reference marsh had 2.3 times the above-ground plant biomass as the 4-5 year-old planted marsh.	PERL 1990
	Fort Lauderdale, FL; rehydrate drained wetland and facilitate water retention in a cypress forest.	Pre-post comparison	Pre: no cypress seedlings Post: 35 cypress seedlings Suggests rejuvenation of forest processes.	Weller 1995

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Port Marsh, NC; dry dredge spoil graded to create *Spartina* marsh.	4 years	Rapid *Spartina* growth; in 3 years, biomass and stem densities = natural reference marsh.	Levin et al 1995
	USACE spoil disposal sites; six locations (1974-1982); marsh habitats on dredge spoil.	Various	At 4 sites, plant communities were more productive than nearby reference marshes.	Newling and Landin 1985
	Camargue, France; ricefields converted to freshwater marsh.	1989-1991	Veg. communities differed according to treatment (flooding vs non-flooding).	Mesleard et al 1995
	Hayward, CA; salt evaporation pond converted to tidal marsh.	1981 May-June	One year after breaching, vegetation was growing on margins, particularly at 2.4 to 3.0 m MLLW.	Niesen and Josselyn 1981
	Campbell River, BC; artificial islands constructed in river channel.	1982-1986, May-July	Aerial coverage after 4 years was from 50 to 90 percent.	Levings and MacDonald 1991
	Indian River, FL; impounded planted wetlands replanted.	1989-1991	Biomass comparable to natural marsh.	Ecoshore, Inc. 1992
	Lake Ripley, WI; water levels manipulated to create pike habitat.	1964-65	Cattails dominate flooded area, with sedges along edge.	Kleinert 1970
	James River, VA; freshwater intertidal wetland constructed out of dredge spoil.	1979-1983	Natural colonization occurred, but wash out was a problem during flood stages.	Landin et al 1989

D-022677

D-022678

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	York River, VA; upland area excavated to intertidal elevations.	Summer 1992	Five years post project, species composition was similar to reference marshes, but stem density, percent cover, and root-zone carbon were higher in natural marsh.	Havens et al 1995
	San Diego, CA; island/marsh complex created by grading and excavating uplands.	1-time comparison with ref. marsh	Plant decomposition rates similar in constructed and natural marsh.	Rutherford 1989
	Norfolk, VA; sampling program of constructed and natural marshes.	1-time comparison	Marsh plants slightly more productive and denser at constructed marsh than at natural marsh.	Feigenbaum et al 1989
	Anaheim Bay, CA; tidal marsh island complex created within Seal Beach NWR.	1990-1995	Characteristic species occurred at all sites; natural marsh had higher abundances.	MEC Analytical Systems, Inc. 1995
	North Carolina, various locations; study of planting regimes on dredge spoil.	1987-1990	*Spartina* and seagrass beds were successful and density increased, except for a few sites where erosion and hypersaline conditions occurred.	Fonseca et al 1996

D—022678

D-022679

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Chesapeake Bay, MD; water management and wastewater treatment program.	1980's	Improved water quality increases submerged aquatic vegetation which trap suspended sediments and further improve WQ.	Jordan et al 1991
	Tampa Bay, FL; restore tidal flow to a mangrove-rimmed bay.	13 months pre and 2 months post proj.	Sparse patches of seagrass restored.	Vose and Bell 1994
	North Carolina; *Spartina* marsh on dredge spoil.	1973 and 1986	Mixed marsh vegetation in upper elevation zones, with *Spartina* dominance in lower elevation zones; resembles natural marsh.	Cammen 1976 Sacco et al 1988 Sacco et al 1994
	Carteret County, NC; eelgrass planted on large, barren shoals consisting of fine sands.	1986-1987	Planted eelgrass was subject to damage from wave-driven erosion, but a seed set from the original plantings covered the rehabilitation sites; abundance similar to natural reference sites.	Fonseca et al 1990

D-022679

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Coastal Kelp Forests, various locations; 200 kelp rehabilitation sites using a variety of methods.	NA	Kelp are difficult to establish, particularly where underlying turbidity and sedimentation problems are not first addressed. Kelp beds can be established, over time, with a variety of techniques.	Schiel and Foster 1992
	Tampa Bay, FL; seagrass restored to an area previously occupied by this species.	1987-1989	Seagrass (*Halodule wrightii*) densities $\geq$ 17 year old reference beds. Organic matter in sediments equivalent.	Bell et al 1993
	China, various locations; general review of 2000 case studies.	NA	Authors note Chinese develop managed wetlands and marshes, in a variety of hydrologic zones, for food production and pollution control. Chinese have a significant history of success in restoring wetland functions, wetland plant communities, and aquatic faunal communities.	Mitsch et al 1993
	San Diego Bay, CA; soil supplementation used to support cordgrass marsh growth.	NA	Soil amendments accelerated cordgrass growth.	Joy Zedler 1992
	Pine Knoll Shores, NC; rehabilitation of a *Spartina* fringe marsh.	10 years	Marsh is self-sustaining over a period of 10 years.	Seneca and Broome 1992

D—022680

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Liverpool, England; enclosed dock areas used as hatcheries following WQ and invertebrate introductions.	2 years	Mussel introduction enhanced water quality, allowing salmon to be reared and creating a commercial mussel harvest.	Hawkins et al 1992
	Hackensack River, NJ; tidal influence restored to marsh area, with *Spartina* planted.	6 months	Rapid vegetation growth: *Spartina* and other salt marsh species	Kraus and Kraus 1986
	Pine Creek, Connecticut; tidal influence restored to diked landfill.	5 years	Cordgrass community re-established; phragmite grasses declined 80%.	Steinke 1986
	Savannah River Nuclear Plant, SC; marsh created to receive effluent from a power plant.	3 years	Emergent wetland species of all types increased steadily.	Hooker and Firth 1989
	Hilton Head, NC; rice field converted to wetland to receive wastewater for recharge.	3 years	44 plant species identified, with distinct assemblages depending on distance from effluent source.	Knight and Ferda 1989
	Seagrass and mangroves, various sites; review of 75 seagrass and 200 mangrove rehabilitation efforts.	NA	Author notes many successes in both habitats. Notes that establishment problems associated with wave action are a major problem.	Thorhaug 1990

D-022681

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Fraser River Estuary, BC; review of 50 marsh projects in this area.	NA	Above-ground biomass for restored marshes can be higher than for natural marshes.	FREMP 1995
Lake Systems	Lake Shenipsit, Connecticut; aeration of lake.	1993	Immediate decline in Cyanobacteria noted.	Kortmann et al 1994
	Medical Lake, WA; phosphorus cycling reduced with application of aluminum sulfate.	1977	Phytoplankton, blue-green algae crop reduced and green algae and cryptophytes replace them.	Soltero et al 1981
	Lake Peoria, Illinois; breakwater protection for aquatic habitat.	1987-88	In protected areas, all plantings grew.	Roseboom et al 1989
	Rice Lake, WI; wild rice reestablishment project in shallow lake.	2 years	Plantings of tubers, root stocks, and shoot bundles did not grow well. Seeded wild rice plots grew and re-seeded themselves, density = 47 stems/m^2.	Engel and Nichols 1994
	Lake Tohopekaliga, FL; removal of sediment blocking access to a large impounded wetland, flood control area.	3 years	Aquatic vegetation densities returned to pre-operational conditions -- monoculture of *Typha* sp.	Moyer et al 1995

D-022683

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Lake Puckaway, WI; water clarity and shoreline erosion improved by manipulating water levels and removing carp.	1977 and 1991	Increased growth of submerged aquatic vegetation (water clarity improved).	Congdon 1993
	Santa Barbara, CA; vernal pool creation project.	On-going	Created pools inoculated with spoil from natural pools developed similar plant communities (10 of 14 species), but not exotic species problems of natural pools.	Pritchett 1990
	Tampa Bay, FL; review of 20 experimental plots, nine treatments.	NA	Significant variation in density, species composition and height. Plantings take 2-3 years to establish; floodflows can influence success.	Meyer et al 1990
	USA, various sites; review of 17 wetland mitigation programs USDOT.	NA	Wetlands do not fully recreate the function of the natural wetlands, but most rehabilitated wetlands partially accomplished goals and provided significant benefits for fish, waterfowl, and wildlife.	Normandeau Associates 1992

D—022683

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
River Systems	Kern River, CA; rehabilitation of cottonwood-willow riparian.	1986-1987	Revegetation begun; limited monitoring period precludes conclusions.	Hunter et al 1988
	Middle Crow Creek, WY; flow augmentation in ephemeral stream.	1986-1989	Initial increase in sedge vegetation, dependent on depth to groundwater. Herbaceous vegetation shifted toward water tolerant plants, densities increased in dry meadows with elevated GW levels.	Henszey et al 1994(a) Henszey et al 1991(b)
	Lower Colorado River, NM; re-establish native streambank plants; remove tamarisk.	84 months	Native species reestablished.	Anderson and Ohmart 1985
	Camp Creek and Bear Creek, Oregon; removal of grazing along creeks; replanting and bank stabilization.	1965-1990, every 5 years	Native grasses, sedges, willows, and rushes have replaced barren dirt; successful rehabilitation of SRA.	Hunter 1991

D—022684

D-022685

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Commencement Bay, WA; landfill recontoured for fish and wildlife habitat.	N/A	Variety of riverine and estuarine habitats established.	Shreffler, Simenstad, and Thom 1992
	Hotophia Creek, Mississippi; willow posts and flow deflectors installed.	1 season	Willow riparian recovered rapidly, even with competition from kudzu.	Shields, Cooper, and Knight 1993
	Ohio, two sites; streams were re-structured with riffles, rock deflectors, and rock sills.	NA	Rooted macrophytes established, constricted flow and deepened the channel, and provided a substrate for invertebrates.	Carline and Klosiewski 1985
	Oconto River, WI;	Various	Aquatic plants and macroinvertebrates increased after flow reduction.	Rost et al 1989
	Sevier River, Utah; grazing excluded and riparian planting.	NA	SRA recovery is occurring; best where topsoil is better.	Gourley and Lillquist 1993
	Wisconsin; various streams; 22 habitat improvement regimes.	NA	Willow stakes and wattles worked better than willow poles for SRA.	Wisconsin Tech. Bull 169 1989
	Aurora, Colorado; overbank flooding restored to channelized creeks.	1 year	Created wetlands adjacent to creeks invaded by cottonwood, thistle, and clover.	Gildersleeve et al 1989

D-022685

Habitat Type	Proj. Location/Description	Monitoring Period	Results	Reference
	Blanco River, Colorado; meander corridor restored with seasonal overbank flooding.	NA	Willows and cottonwoods have colonized in response to the altered hydrologic regime.	Berger 1992a
	Illinois River, ILL; pollution control program to restore water quality.	20 years	Submerged vegetation has not responded to improvements in water quality due to continuous resuspension of sediments from boat wakes and wave action.	Sparks 1992
	James River, VA; island and wetland complex created in lower river channel.	5 years	Island and vegetation have evolved in form, and in community composition, in response to flood flow forces. Several distinct communities have developed.	Landin and Newling 1988
	Pacheco Creek, CA; cattle removed from creek area.	1985	Young sycamores and willows increase.	Smith 1989
Reef Systems	Poole Bay, England; block reef created.	4 months	Red algae colonization within one month of reef placement; erect hydroids also observed in one month.	Collins et al 1990
	Kaneohe Bay, Hawaii; reef restored and protected following destruction from explosives work in WWII.	50 years	This reef is now a major tourist attraction, with a robust and diverse reef community.	Maragos, J.E. 1992

Table 4. Response of Fish and other Aquatic Animals to Habitat Rehabilitation

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
Wetland	Cache Slough, SJR Delta, CA; breaching of a leveed island to restore tidal influence.	1991-1993, Spring	13 species collected in the flooded island, including high CPUE of delta smelt; delta smelt females had eggs and males were running milt, suggesting spawning.	Lindberg and Marzuola 1993
	SJR Delta, CA; Donlon and Venice Cut island levees breached and habitat restored on dredge spoil.	1987-1989	122 bird species, 23 fish species used the habitats; abundance of species increased each year; use by outmigrating salmon smolts and by splittail juveniles documented.	England et al 1990
	Rancocas Creek, NJ; freshwater tidal wetland constructed.	1986-1987	Schools of fish observed using the marsh at intertidal periods and low tide.	Caiazza 1989
	Puyallup River, WA; convert landfill to marsh/wetland.	Five years	Juvenile salmon captured soon after access was restored -- residence time up to two weeks; bird use high.	Brostoff and Clarke 1992
	Humboldt Bay, CA; convert sawmill log pond to tidal marsh.	1981-1982	Higher fish abundance and density than at natural reference marsh; reference and mitigation marsh had different communities due to different elevations/depths.	Chamberlain and Barnhart 1993

D-022687

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Maine; natural hydrology restored to impounded brackish marsh.	Five years	Marsh colonized, but abundance lower than at natural reference marsh.	Dionne et al 1994
	Hayward, CA; restore tidal action to diked salt pond.	1 year	Benthic invertebrate colonization was slow; early amphipod colonization was followed by polychaete worms and bivalve molluscs.	Niesen and Lyke 1981
	Bolsa Chica Marsh, CA; restore tidal influence to 150 acres of marsh.	3 years	Fish species increased from 3 to 32 in three years; spawning use documented for 5 species; bird species and diversity have increased.	Novick and Hein 1982
	Florida, several locations; tidal influence restored to diked salt water marsh.	NA	22 species (42,000+ individuals) captured in the impoundment area.	Rey et al 1990
	Newport River Estuary, NC; pine forest graded down to intertidal levels and planted with *Spartina*; dredge spoil graded and planted with *Spartina*.	1987-1989 1991-1993	Initial monotypic colonization (93% annelids) followed by diversity of community; mitigation marsh was distinct from natural reference marsh. After 4 years, macrofaunal densities remained 3 times higher in natural than in rehab. marsh.	Moy and Levin 1991 Levin et al 1995

D—022688

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Stonington, CT; restore tidal flushing to an impounded brackish marsh.	13 years after rehab.	Indicator species (snail and mussel) distribution similar in natural and mitigation marshes; mussel and snail density were 7 and 2 times lower in mitigation marsh, respectively. Fish assemblages in ditches were similar (killifish - mummichogs dominate), and stomach contents indicated similar foraging patterns, but lower consumption in rehab. marsh.	Peck at al 1994 Allen et al 1994
	Seal Beach, CA; upland restored to intertidal zone up to 10 feet deep.	2.5 years and 5 years after rehab	High densities of fish and benthic invertebrates present; bird use high.	Purcell and Johnson 1992
	Florida, 22 locations; comparison of mitigation marshes to natural reference marshes.	NA	21 created marshes supported at least 5 of the 8 most common fish species of natural marshes; site-to-site variations were observed for fish and invertebrates.	Roberts 1991
	Michigan, 11 locations; monitoring of rehab. wetlands.	5 years	Invertebrates colonize within months, with diversity similar to natural marshes; fish and amphibian populations also develop rapidly; reptiles are slower to colonize.	Tilton and Denison 1992

D-022689

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Pointe Mouillee, Michigan; barrier island built to protect restored marsh.	1993-1994	Invertebrate assemblages similar at rehab. marsh and reference marsh, but abundance lower at rehab. marsh; larval and juvenile fish dominate rehab. marsh vs adults and a different assemblage at reference marsh.	Dibble, Hoover, and Landin 1995
	Conesus Lake, NY; wetland ponds created adjacent to river inlet.	1992-1994	Northern pike spawned, and abundance and size of larval pike greater than at natural wetland.	Morrow et al 1995
	Galveston Bay, Texas; saltmarsh created on dredge spoil.	1987-1988	Crustaceans dominated free-swimming populations; shrimp and polychaetes more dense near channels, as were fish. Elements of the community similar to natural reference marsh.	Minello, Zimmerman, and Medina 1994
	Gulf of Texas, various locations; comparison of rehab. marshes to natural marshes.	Spring 1986, 2-5 years after rehab	Invertebrate densities higher in natural marshes, sometimes significantly; infauna density correlated with marsh age. Fish densities and diversity approximately equivalent; site-to-site variability.	Minello and Zimmerman 1992

D-022690

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Galveston Bay, Texas, various locations; comparison of 10 rehab. and 5 natural marshes.	3-15 years after rehab	Created marshes supported lower numbers of natant macrofauna. Densities and production not related to marsh age.	Minello and Webb 1993
	Winyah Bay, SC; *Spartina* marsh established with dredge spoil adjacent to main channel.	4-8 years after rehab	Macrofaunal assemblages similar at old and younger site, as were fish and shell fish assemblages. Densities greater at older site.	LaSalle et al 1991
	Pascagoula, Mississippi; upland converted to intertidal marsh through excavation.	1992-1993, 7 years after rehab	Higher species diversity in rehab. marsh than natural marsh, but assemblages similar -- macroinvertebrates, and fish. Within-site differences in community observed. Bird and mammal use also equivalent.	LaSalle 1995
	Central Florida, various locations; compare fish community in 5 rehab. marshes to 8 natural marshes.	1991-1992	All fish species in natural marshes also found in rehab. marshes, with additional species in rehab. marshes; similar assemblages with some differences in abundance.	Streever and Crisman 1993

D-022692

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Tacoma, WA; landfill converted to marsh along river.	7 years	Immediate colonization by benthic invertebrates, with rapid increase in density; fish diversity and density increased more slowly; transient species use increased, suggesting habitat functions as foraging and refuge from predation for outmigrating salmon smolts. Smolt residence times up to 43 days.	Simenstad and Thom 1996 Shreffler, Simenstad, and Thom 1990 Shreffler, Simenstad, and Thom 1992
	Chehalis River, WA; estuarine slough created in river delta.	1-time comparison with natural marsh	Juvenile chinook residence times and emigration patterns similar at rehab and natural marsh; growth patterns of smolts were similar; stomach contents lower in rehab. marsh, and number of predators higher. Authors conclude rehab. and natural marsh are functionally similar.	Miller 1993
	Chehalis River, WA; estuarine slough created in river delta.	1-time comparison with natural marsh	18 fish species captured at both rehab. and natural slough and 6 other species at rehab. slough. Epibenthic fauna similar, but higher density in rehab. slough. Diversity higher in natural slough.	Simenstad et al 1992 Simenstad et al 1993

D-022692

D-022693

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	San Diego Bay, CA; intertidal salt marsh constructed on upland habitat.	1989-1990, 4-5 years after rehab	Epibenthic species diversity and density higher in natural marsh vs 4-year-old rehab. marsh. Fish species similar; authors conclude that rehab. marsh was 60% functionally equivalent to natural marsh.	PERL 1990
	Peanut Lake, FL; tidal flushing restored to mangrove-dominated lake.	18 months pre and 18 months post project	Post-rehab. fish assemblage changed significantly; transient species replace resident species, similar to natural marsh.	Motta 1995
	Tampa Bay, FL; comparison of rehab. marshes (1 to 52 years old) with natural marshes.	1990-1991	Relative abundance of species was similar in rehab. and natural marshes; similar fish use and community structure.	Whitman and Gilmore 1993
	Tampa Bay, FL, two bays; restore tidal flushing in mangrove-rimmed bay by breaching dike.	14 months pre and 22 months post project	Fish abundance and biomass <u>decreased</u> following rehabilitation of tidal flow, and assemblage was different from natural site. (decrease in residence times for nutrients??)	Bell and Vose 1992
	North Carolina, several locations; salt marsh on dredge spoil.	1973, March-Nov	Species in soils of planted spoil different from bare spoil; higher production in the natural marsh than in the rehab. marsh.	Packard and Stiverson 1976

D—022693

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Ft. Lauderdale, FL; rehydrate drained wetland and facilitate water retention in a cypress forest.	Pre-post comparison	16 aquatic birds, 21 aquatic animals, and 8 fish species, all resident, were found at the rehab. site.	Weller 1995
	USACE dredge spoil disposal sites, six locations (1974-1982); marsh habitats on dredge spoil.	Various	Wildlife use more intense on restored sites than nearby reference sites. Benthic communities comparable to natural marshes at two sites. Heavy colonization by crabs and fish at several sites.	Newling and Landin 1985
	Hayward, CA; salt evaporation pond converted to tidal marsh.	1981 May-June	Disturbance followers dominated benthic invertebrate communities; 20 species of fish, dominated by 4 estuarine species. Fish-eating birds increased.	Niesen and Josselyn 1981
	Campbell River, BC; artificial islands constructed in river channel.	1982-1986	Rehab. and natural areas share 18 of 26 taxa after 3 months. By 4 years, invertebrate densities were equivalent. By year 3, wild juvenile salmon captured in rehab. habitat in numbers $\geq$ in reference habitats.	Levings and McDonald 1991

D—022694

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Polk County, FL; phosphate mine restored to freshwater marsh.	3 years post project	Greater abundances of Diptera post project; abundance correlated with vegetative cover.	Streever et al 1995
	Indian River, FL; impounded tidal wetlands replanted	1989-1991	Benthic species composition similar to natural marsh, but numbers lower; fish community not like reference marsh.	Ecoshore, Inc 1992
	Lake Ripley, WI; manipulation of water levels in shoreline marsh for northern pike spawning.	1964-65, then 1966	Low fish production (5% of reference area); drainage of site by stream allowed for fish entry and exit.	Kleinert 1970
	Wisconsin, two locations; management of marshes for northern pike spawning.	1969-1973	High fish production.	Fago 1977
	James River, VA; freshwater intertidal wetland constructed on dredge spoil.	1979-1983	Greater wildlife diversity at rehab. marshes than natural marshes; fish population and species diversity higher at rehab. marshes. Some differences in assemblages.	Landin et al 1989

D—022695

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	York River, VA; upland area excavated to intertidal elevations.	Summer 1992	Benthic infaunal structure similar, but abundance higher, at rehab. marsh than at natural marshes; fish species diversity and richness higher at rehab. marsh, probably due to salinity differences.	MEC Analytical Systems, Inc. 1995
	San Diego, CA; island/marsh complex created by grading and excavating uplands.	Comparison with ref. marsh, 4 years after rehab	Natural marsh had more invertebrates (2-3x), but fewer crabs than rehab. marsh.	Rutherford 1989
	Norfolk, VA; sampling program of constructed and natural marshes.	1-time comparison	Rehab. marsh had more benthic invertebrates than natural marsh; similar fish composition.	Feigenbaum et al 1989
	Anaheim Bay, CA; tidal marsh/island complex created within Seal Beach NWR	1990-1995	Invertebrate and fish abundance in rehab. marsh $\geq$ than that of reference marsh; higher abundance of resident species; evidence of nursery habitat use.	MEC Analytical Systems, Inc. 1995 Purcell and Johnson 1992
	North Carolina, various locations; study of planting regimes on dredge spoil.	1987-1990	Natant faunal densities increased at rehab. marshes to = reference marshes; overall faunal densities were lower in rehab. sites.	Fonseca et al 1996

D—022696

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Central Florida, 11 mining locations; constructed wetlands on phosphate mine tailings.	Various	Cladoceran assemblages similar to some natural reference marshes.	Streever and Crisman 1993
	Winyah Bay, SC; intertidal marsh created by pumping dredge spoil into island.	1993, 8 years post project	Invertebrate and fish assemblages were similar to those found in natural marshes along the Atlantic Coast.	Allen 1994
	Puget Sound, WA; rocky intertidal habitat and shallow subtidal habitat constructed.	1991-1993, on-going	Fish observed over mitigation substrates, including juvenile chum salmon and schools of Pacific sand lance.	Cheney et al 1994
	North Carolina, various locations; study of previously created marshes.	NA, some marshes 15 years old	Rehab. marshes and natural marshes had similar component organisms and proportions of trophic groups; total density and density within trophic groups was lower in rehab. marshes.	Sacco et al 1994
	Carteret County, NC; large eelgrass planting on sandy shoals.	2 years	32 fish and 19 shrimp species identified; abundances always higher than for adjacent bare areas. Natural reference eelgrass abundance always higher.	Fonseca et al 1990

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Singapore River; artificial eelgrass beds.	Several samplings	Planted fish held on plastic eelgrass beds.	Lee and Low 1991
	Lassing Park, FL; seagrass plantings on bare intertidal substrate.	1989-1991	Polychaete worm used as an indicator species increased to densities higher than those in nearby natural beds. Evidence of higher survival, suggesting predators had not yet colonized the area.	Bell et al 1993
	China, 2000 locations; review of Chinese use of habitat creation for aquaculture and other functions.	Various	Sustainable populations of fish and wildlife in managed wetlands. Their technology is so well developed that it supports large-scale commercial and home production.	Mitsch et al 1993
	Hackensack, NJ; restored *Spartina* marsh	1 year	Fiddler crab burrows remained stable, with new (smaller) burrows indicating recruitment; greater invertebrate density that natural control site.	Kraus and Kraus 1986
	Fairfield, Connecticut; restore tidal influence to a diked marsh experiencing peat fires.	5 years	Marsh fiddler crabs and ribbed mussels have colonized marsh, and fishing has resumed -- in an area diked for 100+ years.	Steinke 1986

D-022698

D-022699

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Mangrove and seagrasses, various locations; review of 75 seagrass and several hundred mangrove rehab efforts.	Various	Author notes that seagrass faunal communities resemble natural communities within 4 years (only faunal study available); Fish colonization of restored mangrove forests is cited as immediate.	Thorhaug 1990
	Mission Bay, CA; eelgrass planted on sandy substrate.	1 year	Topsmelt dominated initially, but dominance ended as bed matured; community composition and biomass were similar to that at reference site. Some differences in site characteristics, slope and depth.	Hoffman 1991
	Tampa Bay, FL; tests of seagrass plantings.	NA	Faunal abundance higher in natural beds, and varied by species planted.	Meyer et al 1990
	Iowa; several wetlands.	2-3 years following rehab	Early results showed differences between rehab and natural reference sites; later studies indicated higher levels of similarity	Delphey 1991
	Iowa; four wetlands on previously drained lands.	2-3 years after rehab	Wetlands communities trending towards natural assemblages.	LaGrange and Dinsmore 1989
	Ohio; four wetlands restorations.	1-2 years post project	Herps found, even though some conditions at the sites were not conducive to their proliferation.	Lacki et al 1992

Habitat Type	Project Location and Description	Monitoring Period	Results	Reference
	Orlando, FL; large wetland created to receive wastewater.	1987-1989	Species number = to natural wetland, but composition differed; natural system supported more fish, amphibian, turtle, and mammal species; created wetland supported more snakes and lizards.	Burney et al 1989
	Central Florida; strip mine restoration.	3 years	A well-balanced invertebrate community established in 3 years.	Evans 1989
	Coastal Florida; 21 marsh sites.	NA	Properly designed sites served as habitat for animal species normally associated with coastal wetlands.	Roberts 1989
	Sarasota Bay, FL; saltwater ponds on previously drained land.	18 months	Well-designed projects can contribute to fisheries; poorly designed project have negligible value.	Edwards 1994
	Lost Lake, Savanna River; upland interstream area, shallow wetland rehabilitation.	2 years, 2 years after project.	Wetland recolonized and reproduction documented for 1/3 of species identified in area.	Hanlin et al 1994
	Naples, FL; mangrove swamp rehab project; hydrology restored.	1 year	Recolonization without change in adjacent faunal densities. Some differences in species diversity.	Shirley 1992
	San Diego Bay, CA; constructed salt marsh.	4-5 years after rehab	Rehab marsh performs at average 57% of reference marsh functions.	Zedler and Langis 1991

D-022700

D-022701

Habitat Type	Project Location and Description	Monitoring Period	Results	Reference
	North Carolina, two locations; salt marsh restoration areas.	9 months	Different development patterns at the two sites, attributed to elevation differences.	Cammen et al 1976
Lake Habitats	Lake Shenipsit, Connecticut; lake aeration project.	1993	Zooplankton increased and *Daphnia* sp. restored as dominant zooplankton.	Kortmann, et al 1994
	Lake Peoria, ILL; breakwater protection for aquatic habitat.	1987-1988	Number of fish species doubled in vegetated breakwater area (4x weight) compared to untreated control.	Roseboom et al 1989
	Rice Lake, WI; wild rice reestablishment project.	2 years	10 fish species colonize the wetland; muskrats plentiful.	Engel and Nichols 1994
	Eastern USA; wetlands at various locations.	NA	Structures in lakes that provide spawning habitat can increase abundance of target species.	Bassett 1994
	Lake Tohopekaliga, FL; removal of sediment blocking access to a large impounded wetland.	3 years	Drastic drawdowns of the lake which resulted rehabilitated vegetation and fisheries, with largemouth bass being favored.	Moyer et al 1995

D-022701

D-022702

Habitat Type	Project Location and Description	Monitoring Period	Results	Reference
	Lake Puckaway, WI; water clarity and shoreline erosion improved by manipulating water levels and removing carp.	1985-1991	Lake now supports a large and diverse species assemblage -- 40 species, with quality fishery for many species.	Congdon 1993
Riverine Habitat	Sharp Creek, Colorado; grazing exclusion project.	1984, 2 years after fencing	Trout standing crop doubled; more trout in fenced than unfenced areas; non-game component of fishery declines in fenced area.	Stuber 1985
	Norway; rock islands placed to restore pools and habitat diversity.	NA	Fish density increased 4.6x at reference sites and 5.6x at treatment sites. Relocation of fish from adjacent habitat could not be ruled out.	Brittain et al 1993
	Small stream; Queen Charlotte Islands; gabion weirs to stabilize and enhance spawning gravels.	NA	Survival of eggs at rehab. site = survival at reference site; probable improvement over pre-project condition, but not measured.	Klassen and Northcote 1988

D—022702

D-022703

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Wisconsin, 45 locations; gabion weirs and vegetation control were primary focus.	Various	In most cases, trout populations increased; some decreases were associated with increased trout fishing.	Hunt 1988
	Camp and Bear Creeks, Oregon; fencing to exclude cattle and various plantings to stabilize banks.	15 years	Camp Creek is now perennial and supports several species; Bear Creek has trout for first time in generations; incidental benefit of improved grazing outside of the stream corridor.	Hunter 1991
	Nooning Creek, CA; deflectors and rock placed to increase diversity and reduce flow velocities.	NA	Density and biomass of steelhead fry and parr = at treatment and control sites. Failure due to improper design, which could not withstand 7-year flood.	Hamilton 1989
	USA, various locations; a review of stream enhancement efforts.	NA	Many increases in fish density or number recorded, also some declines. Redistribution of fish not ruled out. Many failures were early attempts.	Reeves, et al 1989
	Mack Creek, Oregon; increase of lateral habitat and change in flow velocity.	NA	Coastal cutthroat (only fish in stream) increased in treatment sites; growth data indicate biomass increase.	Moore and Gregory 1988

D—022703

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Streams on South Platte River, Colorado; increase pool to riffle ratio.	NA	Carrying capacity increased by 144-148%.	Stuber 1984
	Southeast Alaska, six streams; habitat (riparian cover) was removed to test importance of SRA.	1 year	Rate of return to experimental areas was lower than for untreated SRA-intact areas. Demonstrates the importance of SRA habitat.	Bjornn et al 1991.
	Vincent Creek, Oregon; pool creation in creek with 1:4 pool to riffle ratio.	NA	More and larger coho salmon (10x) used the treatment segments than the control areas. Cutthroat densities were stable, but size increased, suggesting a biomass increase.	Anderson and Miyajima 1975
	Colorado, various locations; stream habitat improvements.	Various	Some creeks had higher biomass than pre-project; most had variable biomass, but in pre-project range.	Knox 1984
	Melk River, Austria; repair of channelization impacts.	NA	Species increased from 10 to 19; density and biomass increased as well; 15 of 19 fish species were naturally reproducing; benthic taxa increased from 202 to 273.	Jungwirth et al 1993
	River Livojoki, Finland; stream rehabilitation with structural modifications.	1992	Densities of benthic insects increased after a post-rehab. decline.	Tikkanen et al 1994

D-022704

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Tongue River, FL; rearing marsh for northern pike.	1981	80% of pike fry recovered from river were fish reared in the restored marsh.	Florida Coop. F&W Research Unit 1984
	South Creek Estuary, NC; reconstruction of phosphate mines.	NA	48 finfish species found in rehab. areas where no fish were prior to rehab. Note that gear efficiency was variable by species.	Rulifson 1991
	Clarence River, Australia; engineered gates on streams.	1988-1990	Gates to control flows decreased abundance and diversity.	Pollard and Hannan 1994
	Pine River and Mink Creek, Canada; increase meanders, pools, and riffles.	1991-1992	Trout produced in habitat which did not hold trout pre-treatment; eggs scour and drift was reduced and treatment area produced more larvae.	Newberry and Gaboury 1993
	River Gelsa, Denmark; convert 1.3 km channelized reach to 1.8 km meander.	NA	Macroinvertebrate community increased in size and density.	Friberg et al 1994
	Hotophia Creek, Mississippi; SRA and pools rehabilitated.	NA	Fish species increased 90% and mean fish length by 60%; 10x increase in biomass suggests population effect.	Shields, Cooper, and Knight 1993

D—022705

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Ohio, two streams; increase riffles and pools in channelized streams.	NA	Increase in species, abundance, and biomass in sections with structures. Flows may have had impact on results.	Carline and Klosiewski 1985.
	Oconto River, WI; closure of pulp mill; flow reductions.	8 months	Invertebrates increased at all 8 monitoring sites; fish spawning increased as nature of gravels changed.	Rost et al 1989.
	Sevier River, Utah; 2km segment of river restored; grazing exclusion and structural measures.	1 year	Macroinvertebrates recover following rehab. Catchable fish doubled. Trout biomass doubled and nearly tripled for catchable sizes.	Gourley and Lillquist 1993
	Un-Named creek, Quebec; increase pool/riffle ratio from 1:9 to 1:1.	NA	Trout increased 30% and biomass increased 100% Crayfish biomass also more than doubled. Mink and raccoons also increased, 53% and 350% respectively. Suggests sustainable biomass increase.	Gore 1985
	Strawberry Creek, CA; rehab sewers, stop downcutting, repair checkdams, and restock.	NA	Macroinvertebrate species increased.	Charbonneau and Resh 1992

D—022706

Habitat Type	Project Location and Description	Monitoring Period	Evidence of Habitat Use and Population Benefits	Reference
	Virginia, various locations; study of many reclaimed strip mines.	Various	Benthic animals and fish populations significantly lower in reclaimed than natural reference streams.	Matter and Ney 1981
	Louisiana backwater complex; restore flood patterns.	1981-1989	Fish crops increased significantly.	Ewing 1991
	Idaho; Birch Creek; riparian zone restoration.	1-year	Highly engineered project with problems, but trout recolonizing (albeit at lower density than in natural reference stream).	Jensen et al 1987
	Illinois River, IL; pollution control program.	20 years	Sportfishing restored.	Sparks 1992
Multiple Habitats	Chesapeake Bay, MD; reservoir, stocking, and wastewater treatment integrated program.	Various	Trout restored to river below new reservoir; floating pens now used for raising trout for stocking; striper fishing beginning again.	Jordan et al 1991
Reefs	Oahu, Hawaii; placement of concrete-block reef structure.	1 year	Initial colonization by rock oysters, tubeworms, and bryozoans; replaced by slower growing coralline algae. Fish grazed the reef, and community shifted from herbivore dominated to carnivore dominated community.	Bailey-Brock 1989

D—022707

Habitat Type	Project Location and Description	Monitoring Period	Results	Reference
	Grays Harbour, WA; oyster shell reef created.	1986-1988	Juvenile dungeness crabs invaded rapidly, grew to > 30mm CW, and migrated off the reef; suggesting enhanced recruitment.	Dumbauld et al 1993
	Poole Bay, England; block reef installation.	4 months	Post-larval fish arrived within 6 hours, lobsters within three weeks, tube worms immediately. At 4 months, reef community beginning to develop comparable to nearby natural reefs. Foraging, shelter, nursery functions evident.	Collins et al 1990
	Torrey Pines, San Diego, CA; artificial reef.	1-year	Biomass of prey species for sport fish was 100 times that of adjacent habitat; resident fish recaptured at reef site suggest they benefit from reef.	Johnson et al 1994
	Delaware Bay; artificial reef.	2 years	Biomass of sessile species 147 to 846 times greater on reef than on adjacent mud bottom habitats.	Foster et al 1994
	Italy; five Adriatic Sea reef sites.	3 years	Gradual increase in abundance recorded; suggests recruitment in addition to attraction.	Bombace et al 1994
	Southeastern Florida; various sites.	2 years	Assemblages depend on reef size; transient species make up majority of reef biomass.	Bohnsack et al 1994

D-022708

D-022709

Habitat Type	Project Location and Description	Monitoring Period	Results	Reference
	Florida Keys; small reef project.	< 1 year	Increase in numbers of local resident reef fishes, without notable effects on fishes in nearby non-reef habitats.	Alevizon and Gorham 1989
	Costa Rica island reefs; seeding of dead reefs.	5 years	Seeded reefs had new colonies growing, by branching, in 5 years.	Guzman 1991
	Shimamaki, Japan; artificial reefs for production of commercial species.	NA Data base from 1940 - 1986	Octopus catch increased by 4% as a result of reef installations.	Polovina and Sakai 1989
	Ligurian Sea, several locations; artificial reef project.	1979-1986	Sport fishery re-established; increase in use but CPUE is stable.	Relini and Orsi Relini 1989
	Australia, various locations; review of reef building work.	Various	Studies demonstrate immediate FAD functions. Some longer-term studies indicate successional changes in reef communities, with new species colonizing over years.	Pollard 1989

D—022709

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